BAS Integration:

Characterization and Analysis of BAS Torque Capabilities

Presented in Partial Fulfillment of the Requirements for Honors Research

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By

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Abstract

Hybridizing a vehicle can lead to significant increases in the fuel economy and the performance of a vehicle. One hybrid component that can be integrated into a vehicle is a belted alternator starter (BAS). This component is mounted to the engine and belted to the front-end accessories drive (FEAD). One important consideration when integrating the BAS is the torque capabilities of the system. One specific example of a torque capability being investigated is the range can the BAS operate without experiencing belt slip. The goal of this research was to create a mounting solution for the BAS system to fit within a 2019 Chevy Blazer as a part of the EcoCAR competition.

The BAS mount was designed using a combination of NX modeling software and physical measurements. After integrating the BAS, testing could commence. The vehicle was placed on a lightweight chassis dynamometer and various tests were run on the BAS to collect data that would allow for insight into the torque capabilities of the BAS system. The minimum amount of BAS torque needed to initiate engine acceleration from idle speed with the vehicle in drive was found to be 15 Nm. The minimum torque necessary to start the engine was found to be 17.3 Nm. With regards to the belt slip, the speed ratio parameter named was defined to help establish a relationship between the engine and BAS with regards to the FEAD belt. A baseline value was set from experimental data and then compared to the tests ran to look for deviations which would indicate belt slip. As a motor, the BAS experienced belt slip when subjected to 15+ Nm decreases in torque command. The BAS also experienced belt slip when attempting to start the engine. As a generator, the BAS experienced belt slip more commonly. At low vehicle speeds, torque demands combined with driver acceleration caused severe belt slip while at higher vehicle speeds, the BAS experienced significant belt slip at torque demands over 20 Nm.

Acknowledgements

I would like to start off by thanking Dr. Shawn Midlam-Mohler for providing me with the opportunity to perform research through the EcoCAR team as well as continue my education beyond my undergraduate degree in Mechanical Engineering. It has provided me with an opportunity to further my technical knowledge while also gaining experience with project management, both of which will be of great use in my professional career.

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I want to thank Hariharan Rangarajan and Vicen Capito Ruiz for helping me perform tests on the BAS system. Without their help controlling the BAS system, completing testing would have been much more difficult.

I would like to thank my family for supporting me throughout my entire life. It is the love and encouragement given to me by them that allows me to continue pushing forward every day. I have always been told by them that I could accomplish anything and that I had incredible potential. I believe this research is just another testament to the knowledge, confidence, determination, and power they have instilled in me.

Finally, to my Oma, I will never forget the moment you told me you were proud of me which was the last time I got to see you. I will continue to live in a way that makes you proud with this research just being one example.

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Chapter 1: Introduction

1.1. Hybridization and Electrification History in the Automotive Industry

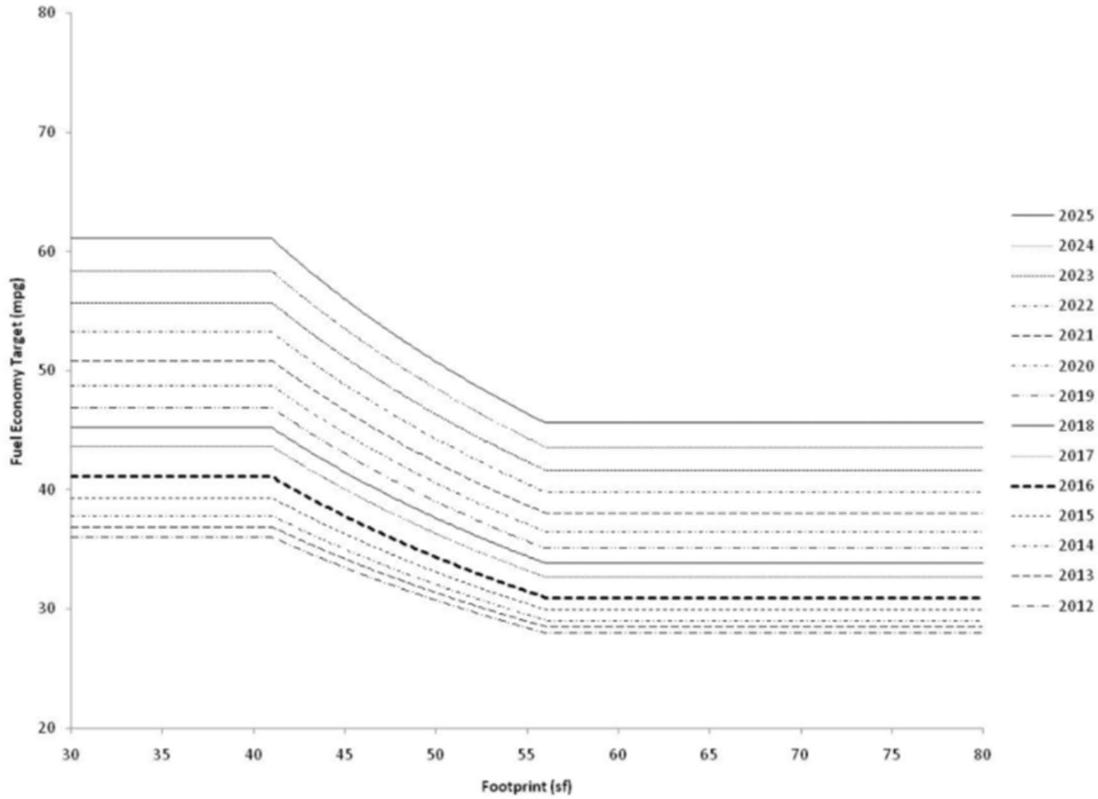
The automotive industry has been evolving at perhaps the most rapid pace seen since the invention of affordable automobiles with the Ford Model T. This evolution is occurring on two differing fronts, one being the development towards fully autonomous vehicles and the other being the hybridization and electrification of vehicles. While vehicle autonomy has become a field of ever-increasing interest, electrification of vehicles appears to be the most prevalent evolution that will be widely adopted by industry. In fact, the roots for this electrification revolution were planted many years ago. In 1996, California introduced a mandate for automakers to have zero-emission vehicles prepared for market by 1998. In response to this, GM introduced the EV1 which served as the first mass-production electric vehicle (Davies, 2016). This vehicle had an underwhelming range of around 50 miles per charge. California ultimately rescinded this mandate and the EV1 failed to penetrate the market which resulted in the program being scrapped by GM. However, this helped lay the groundwork for the electrification revolution being seen now.

The breakthrough of hybrid electric vehicles is often traced to the Toyota Prius. The Prius was released worldwide in 2000 and was considered the first mass-produced hybrid electric vehicle. This vehicle garnered attention from celebrities which helped increase its profile, leading to the Prius becoming the best-selling hybrid worldwide during the first decade of the 21st century (Matulka, 2014). A large part of the success of the Prius can be attributed to the fact that it was a hybrid vehicle rather than a fully electric vehicle. The battery technology had not evolved to a point where fully electric vehicles were a viable substitute to standard internal combustion engine (ICE) vehicles. However, combining electric propulsion techniques with ICE propulsion techniques allowed for increased fuel economy in vehicles without completely sacrificing the driving range of said vehicles.

1.2. Purpose of Hybridization

Since the introduction and relative success of the Toyota Prius, there has been an ever-increasing focus on implementing hybrid technology into vehicles for a variety of factors. The most prevalent reason for this hybridization rush has been due to increasing concern over the environmental impacts that vehicles have and the inflating number of regulations surrounding these concerns.

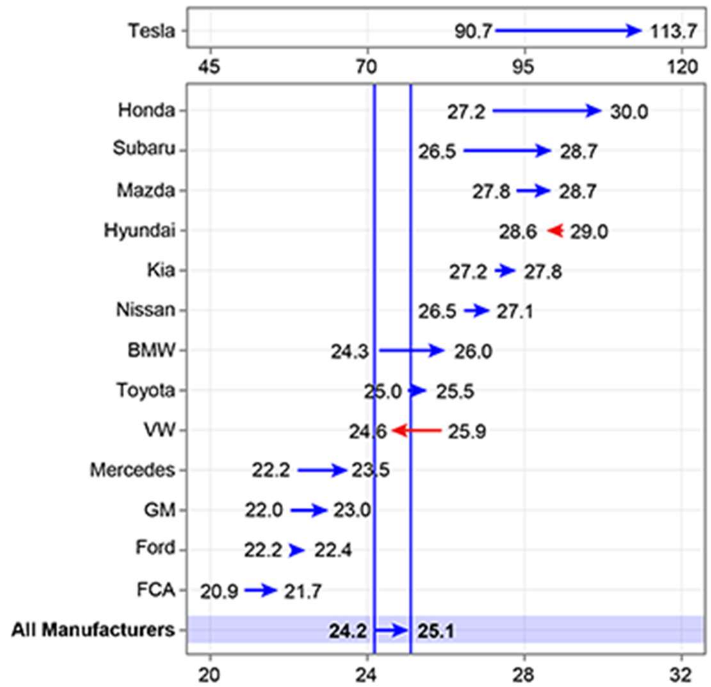
When looking to investigate regulations surrounding automotive vehicles, one can observe the regulations set by the Obama administration in the United States. The Corporate Average Fuel Economy (CAFE) standards were created by the Obama administration to create national standards regarding the fuel economy targets for automakers selling vehicles in the United States. The proposed targets set by the CAFE standards can be observed below (Figure 1).



(Oster, 2019)

Figure 1: CAFE Standards

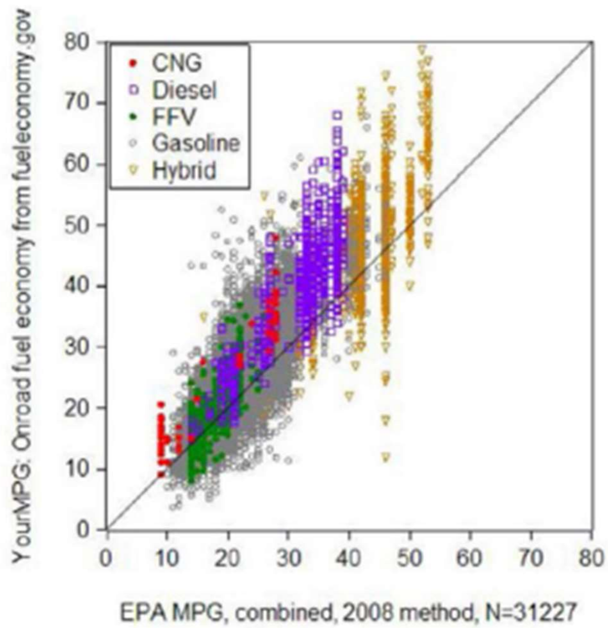
As seen in Figure 1, the fuel economy targets for automotive manufacturers has been increasing at a rapid pace since 2012 and will continue to increase in value. The resulting changes in real-world fuel economy of major automotive manufacturers from 2013 to 2018 due to this increasing fuel economy targets can be seen below (Figure 2).



(Irfan, 2019)

Figure 2: Fuel Economy Changes (MPG) for Automotive Manufacturers 2013-2018

As seen in Figure 2, automotive manufacturers have been able to make some progress towards increasing the fuel economy of their fleet of vehicles. However, there is still significant strides that need to be made to reach the targets outlined by CAFE along with other targets set around the world. While some optimization of vehicle components, controls, and design can be done to increase the fuel economy of ICE vehicles, the best way to dramatically increase fuel economy of a vehicle is to incorporate hybrid technology into said vehicle. A perfect representation of the difference between hybrid vehicle fuel economy and vehicles with alternative fuel types can be observed in Figure 3 below.



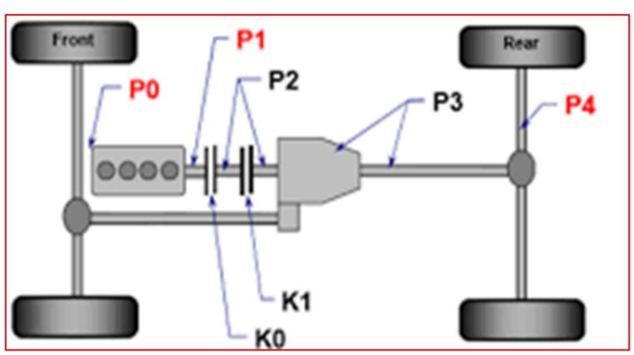
(Thomas et al, 2017)

Figure 3: Fuel Economy of Various Vehicle Fuel Types

Figure 3 clearly displays that the fuel economy of hybrid vehicles far exceeds that of vehicles powered solely by gasoline (ICE) as well as vehicles that use other alternative fuels.

1.3. Hybridization Techniques

There are a variety of paths that can be taken when attempting to hybridize a vehicle. More specifically, there are various places electric motors can be placed to hybridize a vehicle. A high-level overview of some of these locations can be seen below (Figure 4).



(Schaeffler presents high-performance 48V concept mild hybrid vehicle at Aachen, 2016)

Figure 4: Hybridization - Motor Placement

A P0 motor is connected to the crankshaft of the engine via the front-end accessory drive (FEAD) belt. A P1 motor is connected on the other side of the engine directly to the crankshaft of the engine. A P2 motor is located before the transmission of a vehicle while a P3 motor would be located after the transmission of a vehicle. Finally, a P4 motor is connected directly to the axles of a vehicle. Each of these motor locations provide various benefits to a vehicle and can be combined in different configurations to increase the hybrid capabilities of a vehicle.

An example of a potential hybrid layout can be seen in the vehicle architecture for the Ohio State EcoCAR 4 Team's 2019 Chevy Blazer (Figure 5).

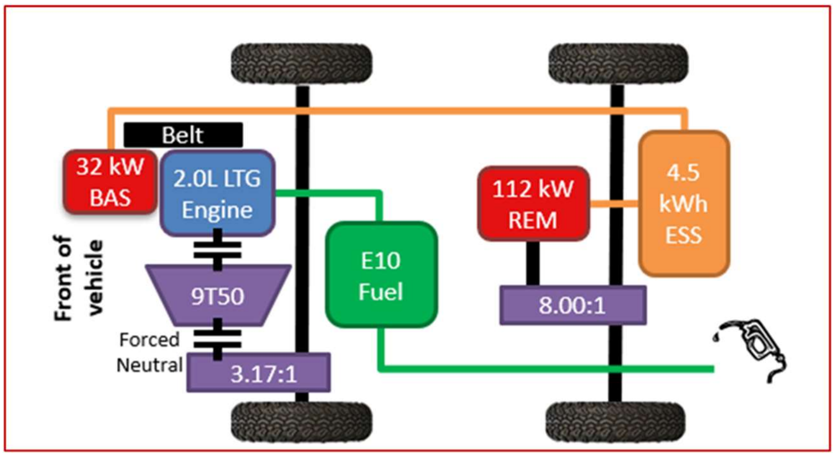


Figure 5: Ohio State EcoCAR 4 Vehicle Architecture

The prominent hybrid components seen in this vehicle architecture include the 32-kW belted alternator starter (BAS) system which serves as the P0 motor. The other prominent hybrid component is the 112-kW rear electric motor (REM) which serves as the P4 motor. This vehicle architecture is the one implemented on the vehicle that was utilized to perform research into the integration of a BAS system. Integrating a BAS system poses a variety of challenges and necessary considerations as well as a variety of benefits when properly integrated.

Chapter 2: Literature Review

2.1. Belted Alternator Starter (BAS) Function

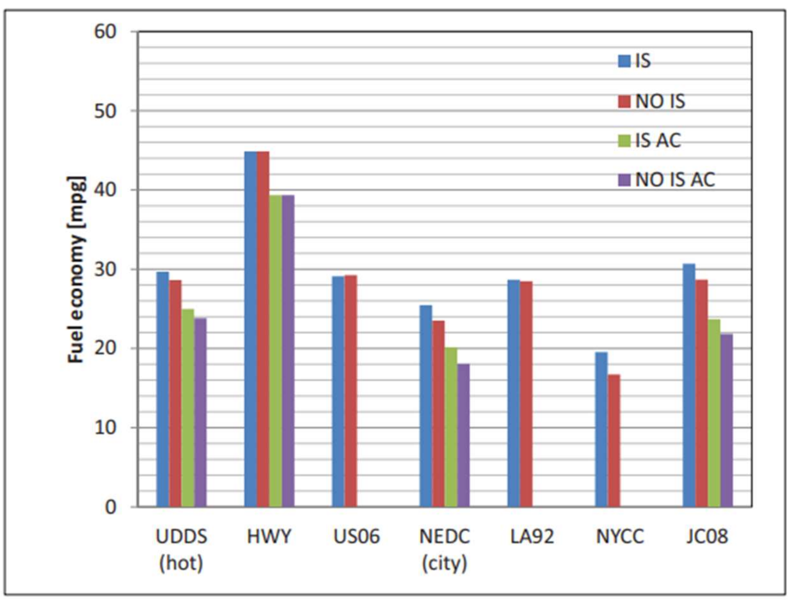
As hybridization becomes increasingly common in the automotive industry, the use of belted alternator starter (BAS) systems in vehicles as well as the research surrounding BAS systems have both increased. BAS systems have also been referred to as integrated starter generators (ISG) in the automotive industry. For the sake of this paper, the system will solely be referred to as a BAS system.

A BAS is an electric subsystem where the functions of starting the engine and generating electric power are performed by one electric machine on-board the vehicle rather than two separated electric machines in a traditional automotive vehicle (Emadi, 2017). In a traditional automotive vehicle, the job of starting the vehicle is left to the starter motor while the job of producing electricity is left to the alternator. Combining these functions into a single electronic machine provides a variety of benefits. Some of these benefits include the ability to produce more power than the conventional electrical generator on a vehicle as well as gaining the ability to perform start-stop functionality for a vehicle. There has been research into a variety of aspects regarding the functionality of BAS systems as well as the optimization of BAS systems, some of which will be touched on in the following Sections. This will not only provide a basis of knowledge regarding the state of research for these systems but also help set the stage for the objectives of the research outlined by the entirety of this paper.

2.2. Effect on Fuel Economy

Much of the research conducted on BAS systems surround the potential benefits that integrating a BAS has on vehicle fuel economy. This aligns with the standard primary purpose of BAS systems which is to increase the fuel efficiency of the vehicle. One such way a BAS system helps increase the fuel efficiency of vehicles is by allowing for the use of start-stop technology. Start-stop technology is the ability for vehicle systems to recognize when the vehicle has been stopped for a short period of time. It will proceed to shut the engine off until the driver takes their foot off the break at which point the engine will start up again, allowing the driver to begin travelling again.

The subject of one piece of research from the Idaho National Laboratory (INL) was to investigate the fuel efficiency benefits of using start-stop technology due to the integration of a BAS system in various vehicles (Wishart & Shirk, 2012). This testing included subjecting the vehicles to a variety of different drive cycles as well as observing the response of the vehicles with and without air conditioning (A/C) running. It is important to note that BAS system is referred to as an integrated starter (IS) in this research. The vehicles were subjected to these different conditions while being driven on a dynamometer. The response for one of these vehicles, a 2010 Mazda 3, can be observed in Figure 6 and Table 1 below.



(Wishart & Shirk, 2012)

Figure 6: Mazda 3 BAS (IS) Fuel Efficiency Effect

Table 1: Mazda 3 BAS (IS) Fuel Efficiency Effect

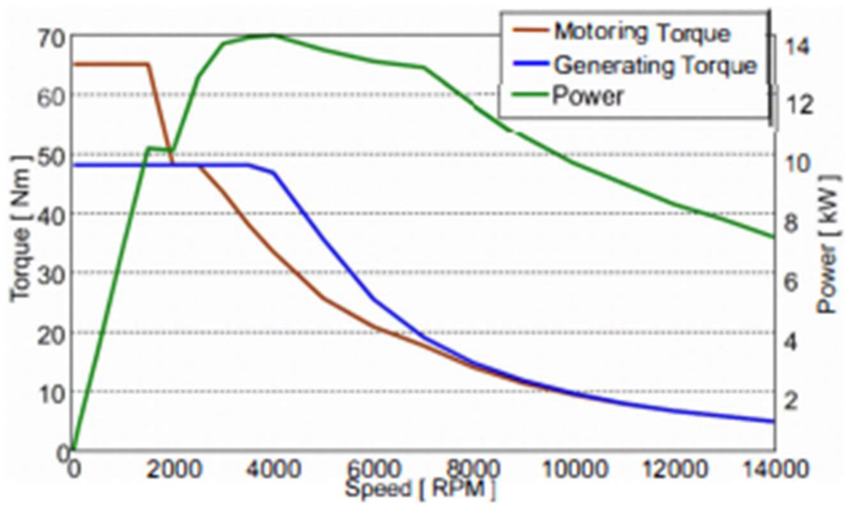
(Wishart & Shirk, 2012)

	Fuel Economy Results (mpg)							
Drive Cycle	IS	No IS	IS A/C	No IS, A/C	Vavg	Stop%	No A/C Comp	With A/C Comp
UDDS (hot)	29.7	28.6	25.0	23.8	19.5	17.8	3.7%	4.9%
HWY	44.9	44.9	39.4	39.4	47.6	0.0	0.0%	0.0%
US06	29.1	29.3	-	-	48.0	6.5	-0.5%	-
NEDC (city)	25.5	23.5	20.2	18.1	11.7	30.6	8.3%	11.6%
LA92	28.7	28.5	-	-	24.6	15.1	0.6%	-
NYCC	19.6	16.7	-	-	7.1	32	16.9%	-
JC08	30.7	28.7	23.7	21.8	-	-	7.0%	8.6%
Calc. EPA City (mpg)	28.6	27.7	% Diff	3.2%				
Calc. EPA Highway (mpg)	44.0	44.0	% Diff	0.0%				
Calc. 5-Cycle (mpg)	27.5	27.2	% Diff	1.1%				

The results (Figure 6, Table 1) show that the integration of start-stop technology when using a BAS system can result in significant changes to the fuel economy of a vehicle under certain driving conditions. For example, when subjected to city driving conditions where the use of start-stop would be more prevalent due to traffic lights and stop signs, the fuel efficiency of the vehicle increased by just over 8% when not using A/C and by more than 11% when using A/C.

2.3. Torque and Power Mapping

Another type of research that has been conducted on BAS systems a variety of times is the torque and power requirements of a BAS system as well as the efficiency at certain operating points. This information is important to the development of BAS systems because it sets the maximum operating range that the BAS system has (assuming ideal conditions for parameters such as temperature) as well as allows for analysis into what operating ranges will optimize the efficiency of the BAS when operating as either a motor or generator. One such example of research was conducted by GM as part of a larger investigation into the design and optimization of a BAS system (Jurkovic et al., 2012). This research established motoring torque, generating torque, and power requirements for designing a 15 kW BAS system. In addition to this, significant operating points were selected and analyzed in terms of the minimum efficiency that should be seen at said operating points. The conclusions made by GM can be observed in Figure 7 and Table 2 below.



(Jurkovic et al., 2012)

Figure 7: GM BAS Torque-Speed-Power Curves

Table 2: GM BAS Significant Operating Points

(Jurkovic et al., 2012)

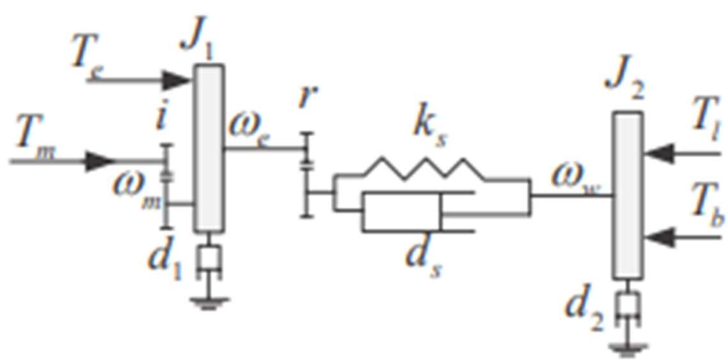
Speed [rpm]	Torque [Nm]	Minimum Efficiency
1200	10	75.2%
1800	7	77.1%
2700	55	72.7%
3000	30	80.1%
3200	8	81.9%
3500	55	72.3%
4800	10	82.5%

Figure 7 provides insight into what the maximum permissible operating range of a BAS system should be as while also showcasing the relationship between peak torque generation and power production. The results seen in Table 2 also showcase that the efficiency requirements of a

BAS system do not appear to be directly proportional to neither rpm nor torque, although it does tend to show that higher efficiencies appear to be desired at lower torques with a moderate rpm value. Perhaps the most crucial takeaway from this research is that the higher efficiency ranges required of a BAS system would correlate to greater fuel economy improvement but not necessarily to vehicle drivability.

2.4. Controls Strategy

The most prominent area of research regarding BAS systems to date outside of the actual designing of BAS systems appears to be developing controls strategies for said BAS systems. These controls strategies vary in their objectives, with some focusing on the optimization of the fuel efficiency benefits provided by the BAS while others focused on other operational aspects of the BAS system. One research project focused on developing a controls strategy for the BAS system that actively damped the drivetrain oscillations experienced by a vehicle (Jiang et al., 2016). To develop this controls strategy, a simplified dynamic model of the drivetrain for a BAS drivetrain was created. This simplified model can be seen below in Figure 8 along with a list of the parameter definitions in Table 3.



(Jiang et al., 2016)

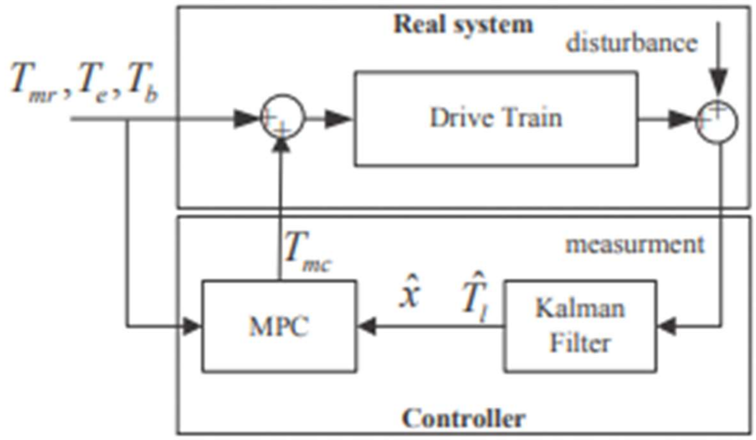
Figure 8: Simplified Hybrid Drivetrain Dynamic Model

Table 3: Hybrid Drivetrain Dynamic Model Parameters

(Jiang et al., 2016)

Parameter	Definition
J_1	Moment of Inertia from motor to differential gear
J_2	Moment of Inertia of remaining driveline
d_1	Viscous friction from motor to differential gear
d_2	Viscous friction of remaining driveline
T_m	Motor Torque
T_e	Engine Torque
i	Belt transmission ratio
r	Gearbox ratio
k_s	Flexibility of drivetrain approx. spring
d_s	Flexibility of drivetrain approx. damping
T_b	Hydraulic brake torque
T_l	Driving resistance torque
ω_e	Engine Speed
ω_w	Wheel speed
ω_m	Motor speed

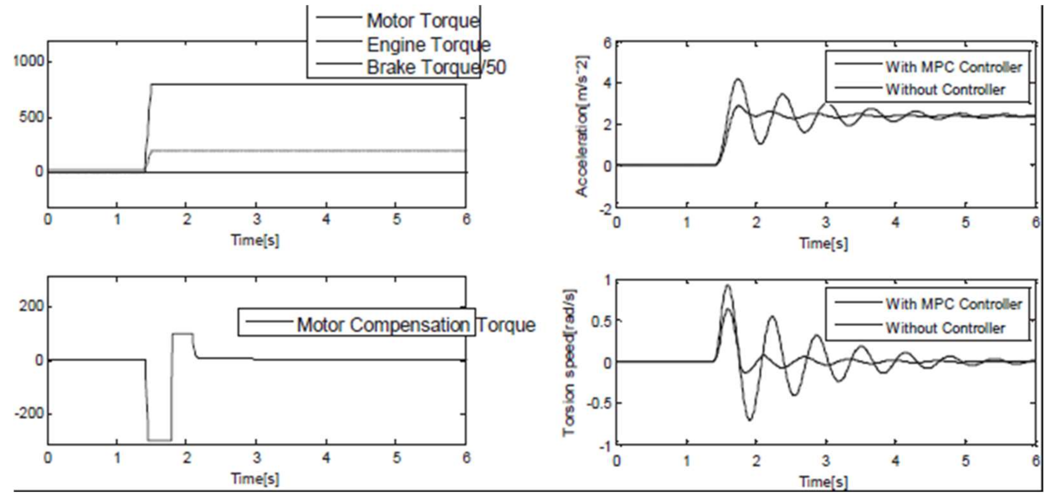
This model (Figure 8) was used to develop the equations of motion for the vehicle drivetrain before placing the system into state space to simplify the development of a controls strategy. The specific type of controls strategy that was chosen was a model predictive control (MPC) strategy due to its ability to solve for the optimization of the system while considering the constraints of a physical system. The overall controls structure that was developed used this MPC approach along with a Kalman filter. The Kalman filter is applied in order to estimate the full state variables. The schema of the overall controls system can be observed in Figure 9 below.



(Jiang et al., 2016)

Figure 9: Schema of control system for active damping

The variable T_{mr} and T_{mc} represent the motor torque demand from the hybrid control unit (HCU) and the output of the controller, respectively. Once this controls strategy was fully developed, the MPC controller was tested and evaluated for a variety of operating maneuvers. These tests were performed in the simulation software Simscape (subset of Matlab/Simulink). Once maneuver conducted was tip-in with motor drive added. The tip-in maneuver is starting the vehicle from a speed of 5 km/h with the engine speed around 1000 rpm before subjecting an engine torque requirement change at 1.5 s from 0 to 800 Nm within 0.1 s. Meanwhile, the motor adds a driving torque around 200 Nm. The results from running this simulated test can be observed in Figure 10 below.



(Jiang et al., 2016)

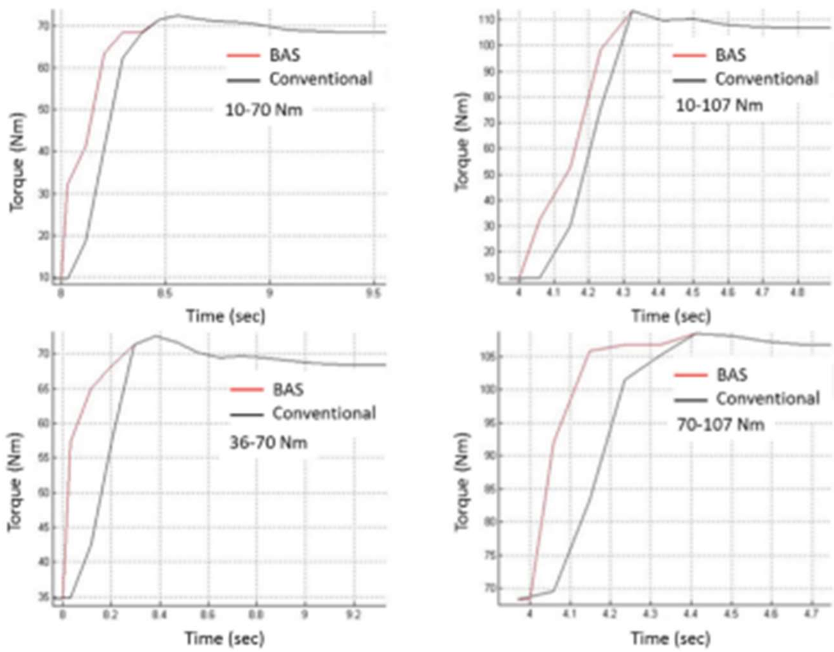
Figure 10: Tip-In with Motor Drive Test Results

As seen in the two graphs on the right of Figure 10, the oscillation seen in the acceleration and torsional speed of the drivetrain are both significantly reduced in both magnitude and duration when the MPC controller is enacted versus having no MPC controller.

2.5. Electric Boost

A BAS system is not solely limited to functions that increase fuel economy and performing the functions of a generator. BAS systems can provide electric boost to assist the engine when attempting to accelerate, thereby improving the acceleration performance of a vehicle. Electric boost in this case is simply providing additional torque to the engine through the BAS operating as a motor.

Research was performed into the additional performance gained when providing electric boost to an engine during acceleration (Raghavan & Balhoff, 2019). More specifically, this research investigated the increase in performance for a vehicle that was using exhaust gas recirculation (EGR). EGR removes a portion of the air in the exhaust manifold and reroutes the air to the intake manifold of the engine. This is done to help increase the fuel economy of a vehicle. For this research, a model of a 4-cylinder engine was created within GT Power along with the presence of EGR flow and a model of a 4 kW BAS system. Once the model was fully developed in GT power, tests were performed to generate torque profiles. These torque profiles had various starting torques along with differing desired torques. These tests were performed both with the engine alone (conventional) as well as with BAS assistance. The results of these tests can be observed in Figure 11 as well as in Table 4.



(Raghavan & Balhoff, 2019)

Figure 11: BAS Assisted Torque Profiles

Table 4: Torque Response Times

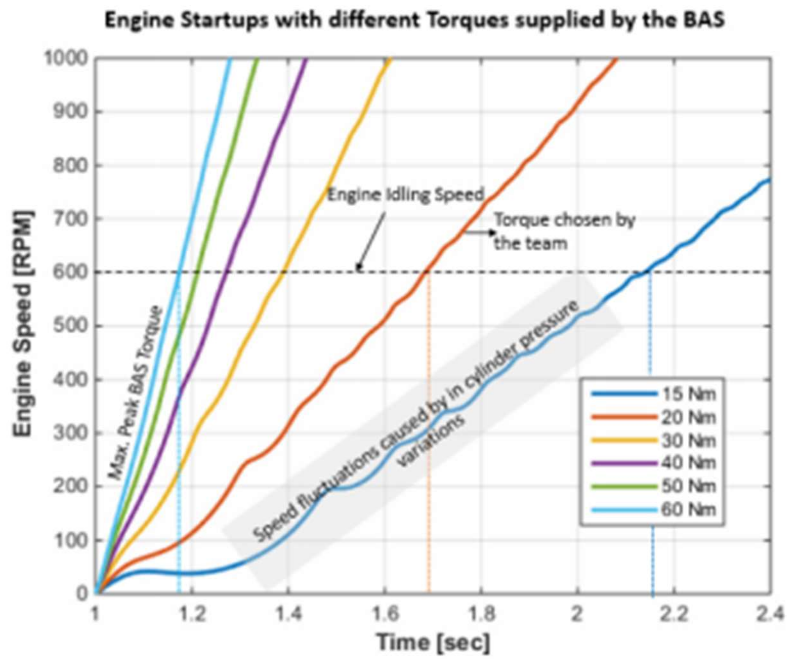
(Raghavan & Balhoff, 2019)

Torque range [Nm] (at 1360 RPM)	3τ response time [sec]	New 3τ response time [sec]	% Improvement
10–70	0.34	0.21	37%
10–107	0.37	0.23	38%
36–70	0.26	0.13	51%
70–107	0.32	0.14	56%

As seen in the test results (Figure 11 and Table 4), the torque time response is drastically better with the BAS providing electric boost versus when just the engine is providing torque. In fact, the least amount of improvement seen out of the 4 tests still saw a significant response time increase of 37%.

2.6. BAS Assisted Engine Startup

One of the primary functions of a BAS system is to be able to start the engine of a vehicle. To do this, a certain amount of torque must be commanded from the BAS to overcome the static load of the engine. This requires analysis into a variety of parameters including the engine dynamics (i.e. compression torque thermodynamics) and engine start torque considerations. One group of researchers utilized this information to develop a model of an engine. They then tested engine startups with varying torques provided by a 32 kW BAS system by hooking up the BAS system to a DC dynamometer that was and simulated the time needed to accelerate up to engine idling speed (Kibalama et al., 2017). The results of this simulation can be observed below.



(Kibalama et al., 2017)

Figure 12: Engine Speed Response to BAS Torque Input

The tests conducted resulted in the selection of a moderate starting torque value due to the desire to limit BAS performance, so the system was capable of being controlled at low BAS torque values. The main drawback of this research is that the response of the BAS torque inputs is determined by a simulation run on a DC dynamometer rather than being a part of vehicle-in-the-loop (VIL).

2.7. Review of Research Literature

The implementation of BAS systems into automotive vehicles is still a relatively new practice, meaning that there is significant interest in learning more about this process and the potential research opportunities in this field are expansive. On the same note, the relative youth of this practice also means the amount of research that has been conducted and completed with regards to implementing BAS systems into automotive vehicles has not been very comprehensive. However, there have been significant strides made in researching various aspects regarding the implementation and optimization of BAS systems such as those seen throughout chapter 2.

One of the most prominent fields of interest regarding BAS systems are the effects these systems have on the fuel economy as seen in Section 2.2. Another important field of research having to do with the implementation of BAS systems into vehicles has been implementing control strategies to optimize some desired performance characteristic of the BAS. For example, the controls strategy research outlined in Section 2.4 focused on optimizing the BAS performance regarding minimizing drivetrain oscillations. Investigating the application of torque as well as the torque response of BAS systems when implemented into vehicles is another crucial field of research. One example of this was seen in the simulated tests run to evaluate electric boost capabilities of a BAS system in Section 2.5.

While the previous research conducted into implementing BAS systems has provided a lot of insight into the simulation of BAS systems and some of their capabilities, there is still a plethora of unknown information. Namely, no research touches on mounting challenges that exist with implementing a BAS system nor is there VIL analysis on the relationship between the operation of the BAS and the operation of the engine. While these results would vary on a case to case basis due variations in vehicles, spacing constraints, engines, and BAS systems, establishing a process that serves as a basis for integrating a BAS into a vehicle is a valuable proposition. This is especially true due to the increasing pace at which hybrid systems are be adopted in the automotive industry as well as interest growing among car enthusiasts regarding implementing systems such a BAS system themselves.

Chapter 3: Methodology

3.1. Overview of Methodology

As mentioned previously, the vehicle being utilized for this research is a 2019 Chevrolet Blazer RS which is also being developed in various other ways as a part of the EcoCAR competition. The EcoCAR vehicle does not have entirely stock components, for part of the competition is to alter the vehicle powertrain to optimize all aspects of the vehicle towards the competition's goals. This includes swapping the engine from a 3.6L V-6 to a smaller 2.0L I-4 engine, adding a large 350V battery pack in the vehicle, and countless other modifications and additions to the vehicle. Some of these modifications included implementing the BAS system into the vehicle which is comprised primarily of the BAS motor as well as the BAS inverter.

The BAS inverter was mounted underneath the vehicle by a previous EcoCAR member. However, the BAS motor itself required a mounting solution which was made more complicated due to the integration of various systems within the engine bay of the EcoCAR vehicle. The presence of these systems made the spacing constraints in the engine bay significantly smaller not to mention the orientation of the BAS is limited due to the need to align properly with the FEAD belt of the engine. A visual of the engine bay of the vehicle can be observed below (Figure 13).

Figure 13: EcoCAR Vehicle Engine Bay

To develop a BAS mount that fit within the mentioned constraints, the CAD program NX was utilized in conjunction with physical measurements.

Once the BAS was installed in the vehicle, a testing plan was developed to gather data regarding the relationship between BAS operation and engine operation. These tests would be performed on the lightweight chassis dynamometer located at the Center for Automotive Research (CAR) which is an Ohio State facility. A picture of the vehicle loaded on the lightweight chassis dynamometer can be observed in Figure 14.

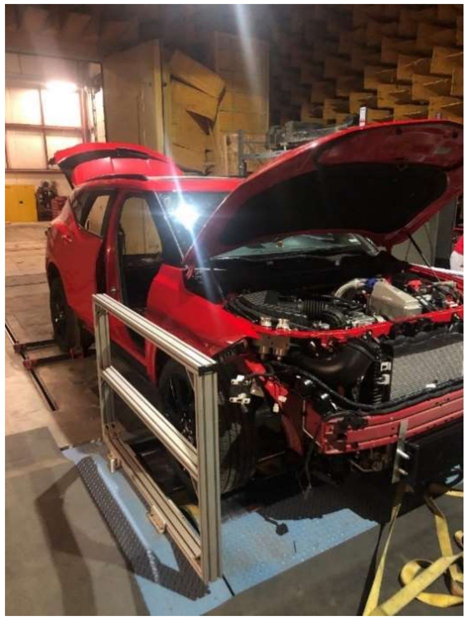


Figure 14: Lightweight Chassis Dynamometer at CAR

The control of the engine speed was done manually with use of the accelerator pedal located within the vehicle while all other controls were carried out by the stock engine control unit (ECU). The BAS system was controlled by a MicroAutoBox located in the cargo area of the vehicle, with controls signals being sent by the user through the dSPACE software ControlDesk. The mounted MicroAutoBox is pictured below (Figure 15).

Figure 15: MicroAutoBox Mounting

The BAS was powered by an external battery system located in the same room as the lightweight chassis dynamometer and is referred to as the AV900. Once the tests were performed and the data was collected, analysis on the test data was completed in the software program Matlab.

3.2. Mounting Strategy

The first step in deciding how to mount the BAS system seen in Figure 16 was determining the point where fasteners could be utilized to secure the BAS. The BAS comes with a variety of flanges that allow for the use of fasteners to secure the BAS either directly to an engine or secure the BAS to some sort of mounting mechanism. Due to the orientation of the engine in the EcoCAR vehicle as well as the lack of mounting locations on the engine, it was decided that a mounting mechanism would be created to interface between the BAS and the engine. Once this decision was made, the development of a mounting solution commenced using a high-fidelity full car model as reference in NX.

Figure 16: BAS Motor

Once an approximate design was developed in NX, the virtual development evolved into hardware-based development. This involved measuring the distance of the first channel for the v-belt ribs on the pulley of the BAS from the face of the BAS. This distance was crucial because it served as the primary driving factor behind the lateral placement of the BAS mount to ensure proper belt alignment. This process also required measurements to validate that the desired angular orientation of the BAS itself would not restrict the operation of the BAS tensioners. Material selection was also investigated during this time where a combination of strength, machinability, and cost were all important factors.

3.3. Testing Plan

As mentioned previously, all testing was to take place on the lightweight chassis dynamometer located at the CAR facility. The purpose of testing on the chassis dynamometer is to allow the vehicle to get up to speed while remaining stationary, making it much easier to implement constantly changing control inputs as well as observe the operation of the systems within the engine bay. The dynamometer did not provide any power to the wheels at any point but rather had the brakes released to allow for rotation of the dyno wheels for when the vehicle was shifted into gear (in drive). A list of the parameters recorded for each test can be observed below (Table 5).

Table 5: Recorded Parameter Values

Parameter	Units
Accelerator Position	Unitless (Decimal Value)
Engine Speed	RPM
Axle Torque	Nm
Estimated Transmission Gear	Unitless
BAS Speed	RPM
DC Current	A
BAS Torque Command	Nm
BAS Torque Response	Nm

3.3.1. Test 1 – Drive with Additive Step Torque Commands - Motor

The first test that was performed started with the engine on and the vehicle shifted into drive. The BAS was operating as a motor for the duration of this test. The engine could reach constant idling speed before any implementation of torque inputs to the BAS. With the engine idling at a constant speed, data began being recorded within ControlDesk. The first torque command sent to the BAS was 1.5 Nm. This ran for an extended period to allow the system to reach a steady state and set a baseline relationship between BAS operation and engine operation. Following this, the torque output command was sent back to 0. The torque output command was then increase by intervals of 2.5 Nm and held there for about 20-25 seconds before taking another step up. This was done until the BAS torque output command reached 15 Nm. This test was conducted to observe the reaction of the vehicle coasting in drive to pure acceleration from the BAS system.

3.3.2. Test 2 – Neutral with Additive Step Torque Commands - Motor

This test consisted of having the engine on and the vehicle shifted into neutral. The engine reached its constant idling speed before any torque commands were sent to the BAS. The BAS, operating as a motor, started at a torque command of 0 Nm and increased by steps of 2.5 Nm. Each command was run for approximately 10 seconds before increasing. This was done until the BAS torque command reached 15 Nm. This test was performed to analyze what happens when using the BAS to accelerate the engine without the vehicle being engaged in drive.

3.3.3. Test 3 – Neutral with Impulse Torque Commands - Motor

This test consisted of having the engine on and the vehicle shifted into neutral. The engine reached constant idling speed before any torque commands were sent to the BAS. The BAS was then subjected to various torque impulse inputs while operating as a motor. These inputs would all start with a torque command of 0 Nm before being sent to the desired torque output value. The various torques commanded from the system can be observed below (Table 6).

Table 6: Test 3 Torque Commands

Command Order	Torque Command (Nm)
1	3
2	5
3	8
4	10
5	11
6	12
7	13
8	14
9	15
10	16

This test was performed to observe how the both the engine and BAS would react to large impulses of torque from the BAS with the engine being in neutral.

3.3.3.1. Neutral with Large Impulse – Motor

When running the tests from Section 3.3.3, reservations about the current limit for the AV900 came up for the final BAS torque command. Therefore, a separate test was run after increasing the current limit of the AV900. This test subjected the BAS to a small torque impulse to ensure the system was functioning properly before sending the desired impulse torque command of 16 Nm to see if there was any noticeable difference in the response with the varied current limits.

3.3.4. Test 4 – Engine Off – Neutral with Iterative Torque Commands – Motor

This test consisted of having the engine off and the vehicle in neutral. The BAS was operating as a motor for the duration of this test. A large torque command was sent to the BAS to attempt to start the engine. Following this, the torque command to the BAS was first reduced and then increased in small steps around the torque command region that saw the engine start. This test was conducted to zero in on the minimum amount of torque needed from the BAS to start the engine.

3.3.5. Test 5 – Various Drive Conditions – Generator

This test consisted of two independent phases. The first phase consisted of having the engine in drive and at constant idling speed while having the BAS operate as a generator. The BAS was then subjected to step increases in torque demand between 1-3 Nm. The starting torque demand from the BAS was 0 Nm and was increased in steps until reaching 35 Nm of demanded torque. Each step would be held for at least 5 seconds before increasing to the next step.

The second phase of this test had a driver in the vehicle pressing on the accelerator pedal attempting to maintain an engine speed around 2000 rpm. The BAS was then subjected to various torque demands while acting as a generator. The initial torque demand from the BAS was 10 Nm before increasing in intervals of 5 Nm. However, before each successive increase would occur (i.e. going from 15 Nm to 20 Nm), the BAS torque demand would be set back to 10 Nm. This was done to attempt to observe if any slip occurred in the belt when experiencing larger impulses of torque demand. Each step would be held for at least 5 seconds before changing torque demand values. The highest torque demand reached for this phase of the test was 30 Nm.

Both tests were done to provide insight into how the BAS and engine responded to varying torque demands from the BAS in what would be either low speed or stationary conditions.

3.3.6. Test 6 – Constant 50 MPH – Generator

This test was performed with the engine on, vehicle in drive, and the BAS operating as a generator. A driver was in the vehicle using the accelerator pedal attempting to maintain a steady speed of 50 MPH. Once the desired vehicle speed was achieved, the BAS started at a torque demand of 0 Nm and increased in steps of 5 Nm until reaching 45 Nm. Once at 45 Nm, the torque demand was then decrease down to 40 Nm before beginning to decrease by steps of 10 Nm until reaching 0 Nm. Each step was held constant for at least 5 seconds before changing the torque demand value. These tests were performed to gain insight on how the BAS and engine would respond to BAS torque demands with the vehicle travelling at high speed.

3.4. Analysis of Test Data

Once testing was completed and all the necessary data was collected, analysis of the resulting data could commence. The overarching goal of any analysis conducted is to help establish the relationship that exists between BAS operation and engine operation. While there is a countless amount of operating conditions for the BAS and engine operating in tandem, the tests conducted and the analysis of the data resulting from these tests provide a solid basis for the relationship that exists between the two mechanisms. The test data for all tests were analyzed in Matlab. The first step was to plot all recorded parameters against time for each test case and put all resulting plots from said test into a single figure.

Following the plotting of all test data came analysis into the relationship of the speeds of both the BAS and the engine. To do this, a new parameter was created and dubbed the speed ratio. The equivalency that defines the speed ratio can be observed below.

$$Speed\ Ratio = \frac{BAS\ RPM}{Engine\ RPM} \tag{1}$$

The purpose of defining this new parameter is to provide insight into the presence of belt slip for any of the operating conditions the engine and BAS system was subjected to. The way the speed ratio allows for this to happen is by observing deviations from a baseline speed ratio value. As mentioned in Section 3.3.1, a small torque command was sent to the BAS system with the engine on and idling while the vehicle was in drive. The system remained in this state for an extended period to allow for the calculation of a baseline speed ratio to which all other tests could be compared against. If the speed ratio at some point during a test differs from the baseline speed ratio by a significant amount, this change would be attributed to the belt slipping near either the BAS pulley or the engine pulley so long as no other major mechanical or electrical issues occurred at said point in time. If the speed ratio increases, this would be due to the belt slipping near the BAS pulley causing a spike in the BAS rpm. If the speed ratio decreases, this would be attributed to the belt slipping near the engine pulley which would cause an increase in the engine rpm. The speed ratio data for all tests except test 5 was analyzed. Test 5 did not have the speed ratio calculated due to the fact this test was focused on overcoming the engine being in a static position, therefore minimizing the importance of a dynamic parameter such as the speed ratio. For each test that did have the speed ratio calculated, a moving average filter of length 5 was applied to help smooth out the data.

In addition to analyzing the speed ratio, each test was observed for undesirable mechanical and electrical responses regarding certain component characteristics. For the engine, the main parameter that was observed with regards to preventing an undesirable response was the engine speed. The maximum engine speed for the 2.0L I-4 engine used was 7000 rpm. In addition to this, analysis was done on the data from the tests were the BAS operated as a generator to see if the engine stalled under any of the torque demands from the BAS system. For the BAS system, various parameters were observed with regards to undesirable responses. On the mechanical side, the BAS has a maximum operable speed of 18000 rpm and a maximum mechanical speed of 21000 rpm. On the electrical side, the BAS has a maximum phase current of 150 Arms. More importantly, to prevent any sustained surges in current, the BAS is connected in series with a 75A fuse.

Chapter 4: Results

4.1. Mounting Strategy

Throughout the process of designing a mount for the BAS, various issues arose. The main issue was interference between the BAS HV connection and a pipe that connected the turbocharger in the vehicle to the intercooler (Figure 17 and Figure 18).

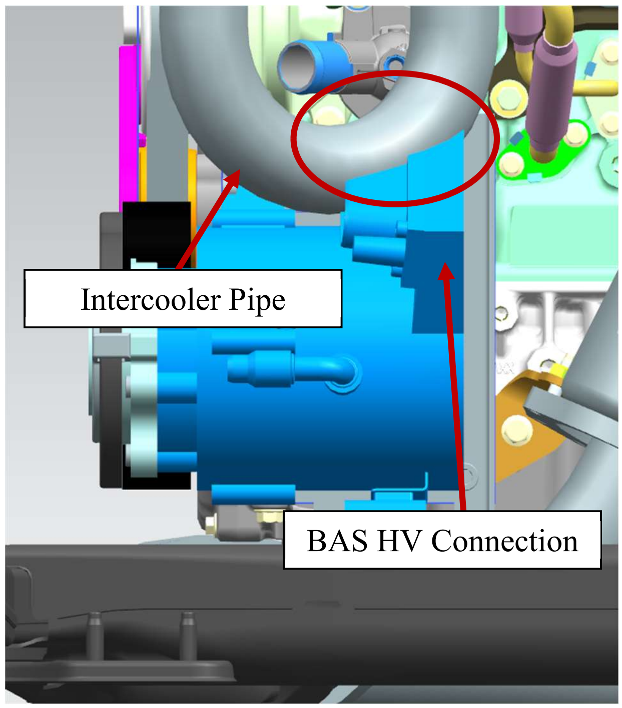


Figure 17: BAS Interference – Left Side View

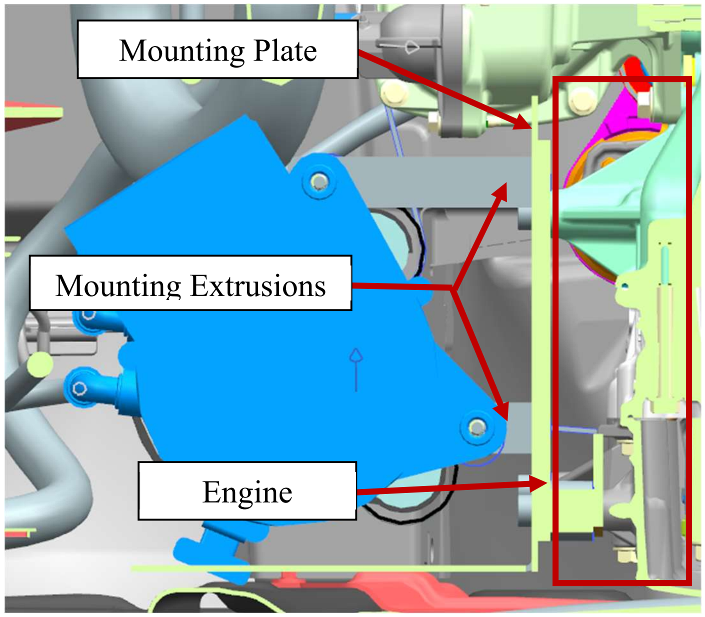


Figure 18: BAS Interference – Right Side View

This interference resulted in the design changes to the intercooler pipe system to provide additional clearance for the BAS while the BAS mount was redesigned to result in the BAS having a greater degree of rotation to help lower the location of the HV connector. This rotation was achieved by extending the length of the two rectangular pieces of extrusion that connect the BAS to the plate mounted against the engine. After this redesign, the first iteration of the mount was machined using aluminum 6061-T6 due to its combination of strength and machinability. The mount along with the BAS was then installed into the vehicle to ensure that there was no interference and that the FEAD belt aligned properly. In addition to this, the tensioner was checked to make sure it maintained the ability to both provide tension to the belt when the system is off and to open up when the belt begins rotating after the engine and BAS turn on. The BAS, upon installation, had full functionality with all components aligned properly and operating as intended. A picture showing part of the BAS and BAS mount can be observed below (Figure 19).

Figure 19: BAS Mounted in Vehicle

4.2. Test Results

4.2.1. Test 1 Results - Motor

The results of the first test for each recorded parameter can be observed in Appendix A. The highest engine speed reached during the test was 1294 rpm which occurred at a BAS torque command of 15 Nm. As expected, this torque command also corresponded with the highest BAS speed observed which was 3447 rpm. The highest current observed during the test was 14.4 A when the BAS torque command was 15 Nm. While none of the listed values were anywhere near the limits proposed in Section 3.4, these values were the result of prematurely shutting the test down due to concern regarding spikes in the speed of the BAS and engine. After both mechanisms maintained a steady speed for every torque command from 2.5 Nm up to 12.5 Nm, the values of both the engine speed and BAS speed began to accelerate quickly at 15 Nm. This acceleration was observed when conducting the experiment and resulted in the premature termination of the test to prevent any potential issues from arising. However, this does provide insight into the necessary torque command needed to initiate acceleration of the vehicle with the BAS system. This could be used in situations where electric boost is desired by supplying the 15 Nm torque command to the BAS when the driver begins to accelerate. Since a motor can provide instant torque, this would allow the BAS to initiate acceleration slightly before the engine also begins producing more power, thereby increasing the acceleration performance of the vehicle.

The beginning portion of the data from test 1 consisted of a constant torque command of 1.5 Nm while the engine idled with the vehicle in drive. This was done to provide data that would allow for the calculation of a baseline speed ratio. The average BAS speed and engine speed was taken over the first 70 seconds of the test data and plugged into the speed ratio equation (1). The resulting speed ratio baseline value was found to be 2.6382.

A plot of the speed ratio for test 1 can be observed below (Figure 20).

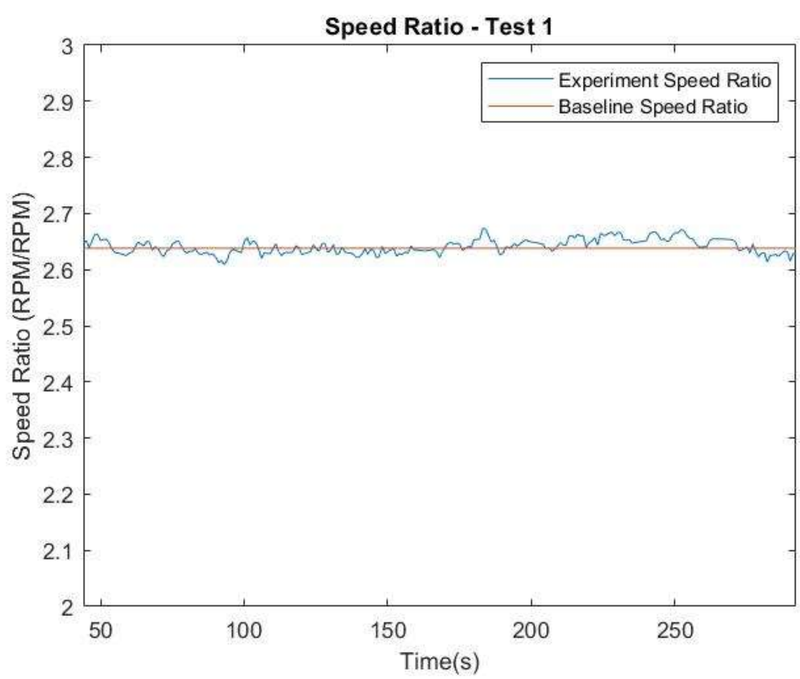


Figure 20: Speed Ratio - Test 1

The speed ratio for the first test stays very close to the baseline value for the entire duration of the test. As a result, it can be assumed that no belt slip occurs under the tested operating conditions. On a broader scale, it appears that supplying lower levels of torque to supplement some of the power created by the engine idling will not result in belt slip.

4.2.2. Test 2 Results - Motor

The results of the second test for each recorded parameter can be observed in Appendix A. The highest engine speed reached during the test was 2392 rpm which occurred at a BAS torque command of 13 Nm. This torque command also corresponded with the largest BAS speed observed which was 6358 rpm. Neither of these values came close to the mechanical limits for their respective mechanisms. However, the current did exceed the limits of the BAS fuse when the torque command reached 13 Nm as seen in Figure 21.

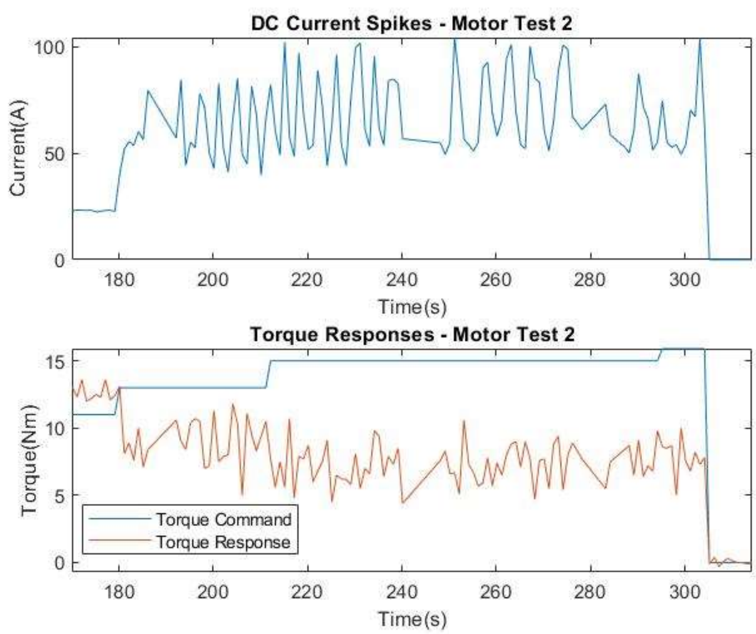


Figure 21: Current Spikes - Test 2

The current begins to oscillate and have peaks of current above the 75A threshold set by the BAS fuse once the torque command is increased to 13 Nm (Figure 21). It is important to note that the fuse is capable of handling current peaks above the 75A it is rate for but only for brief periods of time. Regardless, this behavior is undesirable and therefore any torque commands initiated while the engine is in neutral will want to be kept beneath 13 Nm to ensure the current does not exceed the limits of the system. Based on the torque response of the BAS in comparison to the torque commands (Figure 21), it appears either the BAS system or the system powering the BAS (AV900) may have reached its limits due to the BAS torque response no longer matching the BAS torque command. This reiterates the idea that torque commands should be kept below 13 Nm when the vehicle is in neutral and idling.

A plot of the speed ratio for test 2 can be observed below (Figure 22).

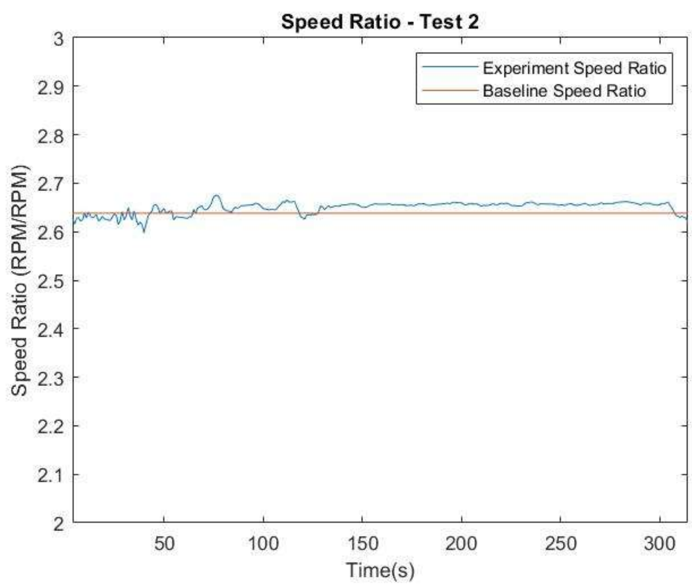


Figure 22: Speed Ratio - Test 2

For the entire duration of the test, it appears the speed ratio remains close to the baseline speed ratio. This would mean that the belt did not slip at neither the engine pulley nor the BAS pulley for any of the torque commands provided to the BAS while the vehicle was in neutral and the engine initially idling. This would mean that in conditions where the vehicle is stationary and idling, the BAS can be used to provide some additional torque to the engine before the vehicle shifts into gear without any belt slip occurring.

4.2.3. Test 3 Results - Motor

The results of the third test for each recorded parameter can be observed in Appendix A. For test 3, the engine speed reached a peak value of 2468 rpm for a BAS torque command of 12 Nm. Similarly, the BAS speed peaked at 6544 rpm for a torque command of 12 Nm. Both values are well below the mechanical limits of their respective mechanisms. The current does spike above the current rating for the BAS fuse like what occurred in the test 2 results. This can be observed in Figure 23.

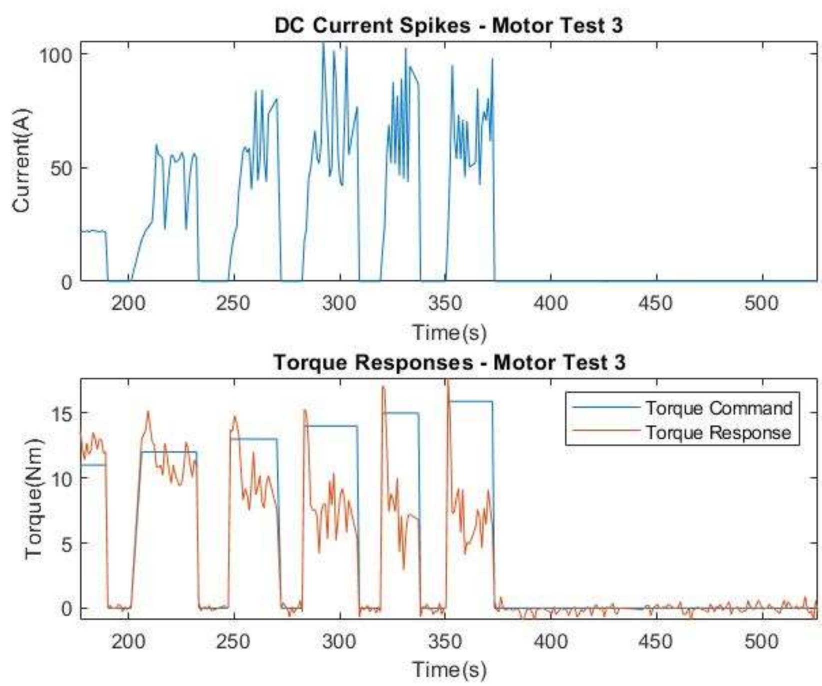


Figure 23: Current Spikes - Test 3

At a BAS torque command of 12 Nm, the current remains well beneath the fuse limit and the torque response closely mirror the torque command. However, upon providing an impulse BAS torque command of 13 Nm, the current spikes above the fuse limit multiple times and the torque response no longer mirrors the torque command. This further supports the notion outlined in the test 2 results (Section 4.2.2) that any torque commands initiated while the engine is in neutral will want to be kept beneath 13 Nm to ensure the current does not exceed the limits of the system.

The speed ratio plot for test 3 can be observed below (Figure 24).

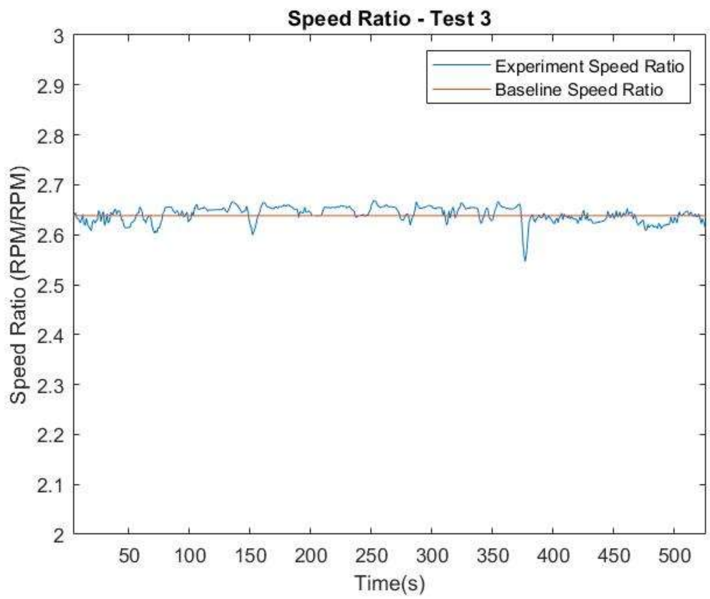


Figure 24: Speed Ratio - Test 3

The speed ratio for test 3 appears to remain close to the baseline speed ratio value besides one instance around 377 seconds into the test. Slightly before this around 374 seconds, the BAS torque command was taken from 15.9 Nm and dropped to 0 Nm. However, the engine remained on with no user input to the accelerator pedal. This caused the BAS speed and engine speed to drop significantly over the following 3 seconds to the point where it dropped slowly below the steady relationship that exists when the engine is idling. This caused a slight rebound in both the BAS rpm and engine rpm during which the belt likely slipped near the BAS. This provides insight into the precautions that may need to be taken when nulling the torque command from the BAS while the engine is operational. If the BAS is providing a substantial amount of torque (15+ Nm), sending the torque command back to 0 immediately will likely result in belt slip. To prevent this, smaller decreases in BAS torque command can be taken intermediately till the torque command reaches 0 Nm.

4.2.3.1. Neutral with Large Impulse Results - Motor

The results from running the 16 Nm BAS torque command after opening the current limits for the AV900 can be observed in Appendix A. The engine reached a peak speed of 3973 rpm while the BAS speed peaked at 10574 rpm. Interestingly the current peaked well below the fuse limit at only 58.9 A. It appears that increasing the current limit for the AV900 allowed for the BAS torque response to closely mirror the BAS torque command. However, this test was cut off prematurely due to the rapid pace at which the engine rpm and BAS rpm was increasing. While neither were necessarily close to their mechanical limits, both accelerated to over 50% of their mechanical limits within 7 seconds and if those trajectories continued, it may have exceeded the limits of the engine and BAS. While the system was able to achieve more stable operation with the increased current limits, the concerns regarding passing the limits of the system is too great and therefore the conclusions reached in Section 4.2.3 are still valid.

4.2.4. Test 4 Results - Motor

The results of each recorded parameter for the fourth test can be observed in Appendix A. The maximum speed of the BAS and engine were 6911 rpm and 2607 rpm respectively. The maximum current drawn was 37.1A. Therefore, none of the mechanical and electrical limits were in jeopardy of being reached throughout this test.

As mentioned in Section 3.3.4, the purpose of this test was to investigate how much torque is needed to start the engine with the BAS. Based on the results, the lowest BAS torque command that resulted in the crankshaft static condition being overcome was 17.3 Nm. However, upon breaking the static condition of the crankshaft, the engine rpm, BAS rpm, and current all begin to increase at a rapid pace. To prevent these values from shooting off into the region of the system limits, the starting BAS torque command of 17.3 Nm should be sent for a brief period of time (1-2 seconds) before reducing the BAS torque command below 10 Nm while the engine begins to operate. This will allow the current, BAS rpm, and engine rpm to settle into steady conditions.

4.2.5. Test 5 Results - Generator

All recorded parameter results for the fifth test can be found in Appendix A. The peak engine speed, BAS speed, and current were 2495 rpm, 6532 rpm, and 35 A respectively. Therefore, none of the system limits came close to being broken.

For the portion of the test were the engine was idling with the vehicle in drive, the engine managed to maintain idle speed for every BAS torque demand up until 24 Nm. The torque demand was the sent back to 0 Nm and subjected to an impulse torque demand of 26 Nm. Such a large increase in torque demand resulted in the engine stalling. Additional testing would be required to determine the limit for a single jump in torque demand. However, this does provide useful insight into the fact that performing intermediate steps when higher torque demand values are desired should be practiced.

Following the engine stalling, small steps were taken back to reach an ultimate torque demand of 26 Nm. At this point, the engine was able to continue operating. However, a very small drop in engine speed was observed around the time the torque demand increased from 25 Nm to 26 Nm. To prevent the any further instances of the engine stalling, a driver lightly pressed the pedal in attempt to maintain the engine idle speed. Following this, the torque demand was increased in steps of various sizes until reaching a peak demand of 35 Nm. The driver was able to maintain the idle speed of the vehicle with an accelerator depression only 10%. Therefore, it seems that it is possible to demand significant torque values when the BAS is acting as a generator without significantly hindering the ability for the engine to operate properly under idling conditions.

A plot for the speed ratio of test 5 can be observed below (Figure 25).

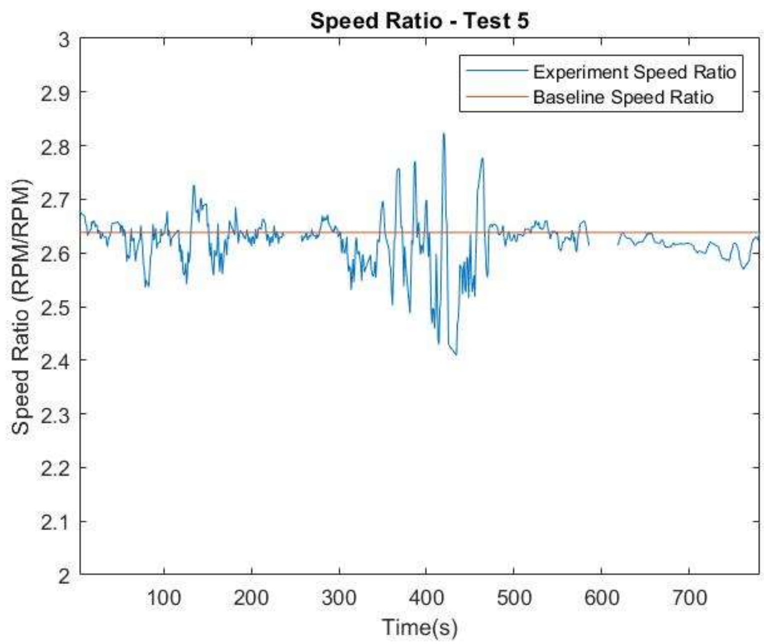


Figure 25: Speed Ratio - Test 5

There are multiple instances where belt slip appears to occur based on deviations between the baseline speed ratio versus the experimental speed ratio. These instances of belt slip correlate closely to the moments where the torque demand is increased. Early in the test (50 s – 200 s), the variations in the speed ratio fluctuate but remain within 0.1 of the baseline speed ratio. This suggests that minor belt slip will occur when altering torque demands from the BAS while the engine operates in low rpm ranges. Later in the test (300 s – 450 s), more significant deviations of up to 0.2 can be seen between the experiment speed ratio and the baseline speed ratio. Again, this appears to be a result of increasing the BAS torque demand. The most significant deviation magnitude of 0.2291 seen at 434 seconds along with the other major deviations that surround this area correlate to the driver in the vehicle slightly pressing the accelerator to help maintain the engine idle speed. Therefore, accelerating the engine while simultaneously increasing BAS torque demand appears to exacerbate the belt slip issues observed when increasing the BAS torque demand at low engine rpm. In addition to this, the BAS torque demand increasing in value in general appears to increase deviation from the baseline speed ratio meaning belt slip is more prevalent.

4.2.6. Test 6 Results - Generator

The results of the sixth test for each recorded parameter can be observed in Appendix A. The maximum engine speed, BAS speed, and current experienced during the test was 2171 rpm, 5723 rpm, and 54.4 A respectively. None of these values were alarmingly close to the system limits. Also, with the driver maintaining a speed near 50 mph, the speed and power provided by the engine was greater. As a result, the risk of stalling the engine such as what occurred in test 5 was not an issue.

The plot for the speed ratio of test 6 can be observed below (Figure 26).

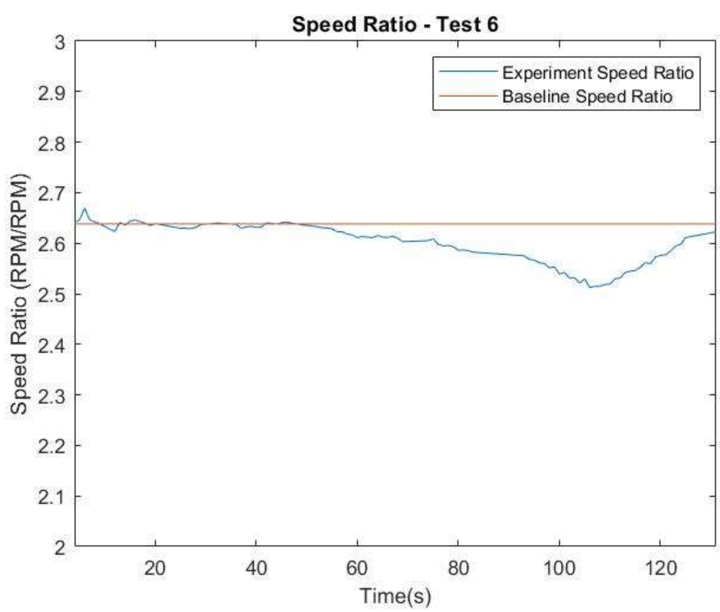


Figure 26: Speed Ratio - Test 6

The experimental speed ration managed to stay within range of the baseline speed ratio for the first 60 seconds of the test, over which period the maximum torque demand from the BAS was 10 Nm. Following this, the experimental speed ratio begins to decrease with a shape that resembles a concave down parabolic curve. The largest deviation between the baseline speed ratio and the experimental speed ratio was .1259 and occurred at the most significant BAS torque demand which was 45 Nm. This indicates that when the vehicle is travelling at higher speeds, increases in torque demand will result in increases to the belt slip occurring in the system. Since the speed ratio is decreasing, it seems the belt is slipping near the engine pulley rather than the BAS pulley. It appears under these circumstances that a BAS torque demand of 20 Nm would be the maximum torque demand that the system can operate under before experiencing significant levels of belt slip.

4.3. Additional Speed Ratio Analysis

To provide a more wholistic view on the results from the speed ration analysis, the speed ratio data for the tests were combined so that any general trends in the speed ratios would become evident. Using Matlab, a histogram was created to represent the frequency at which certain ranges of values appeared across the aforementioned tests. This histogram can be seen in Figure 27 below.

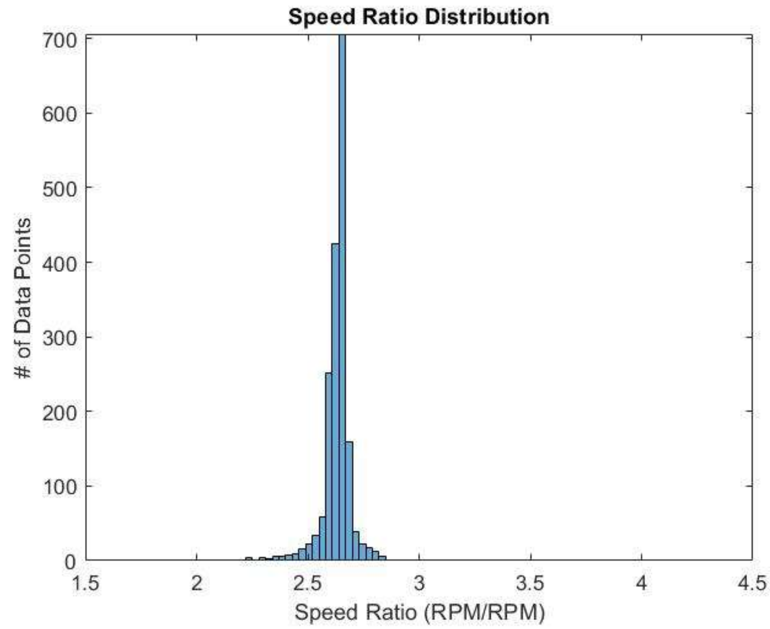


Figure 27: Speed Ratio Distribution

From this data, the mean and standard deviation of the speed ratios was calculated and found to be 2.6301 and 0.1077 respectively. It is worth noting that the baseline speed ratio of 2.6382 that was calculated was close to that of the mean from the combined speed ratio data, thereby validating the use of the baseline speed ratio value for comparisons to the test data. With the standard deviation of the speed ratio now known, the data for all tests were analyzed to determine points where the speed ratio exceeds a magnitude difference of 2 times the standard deviation. At these points, the BAS speed and BAS torque response was then recorded and plotted against each other to provide insight into the BAS operating points that seem to result in belt slip. The results of this analysis can be observed in Figure 28 below.

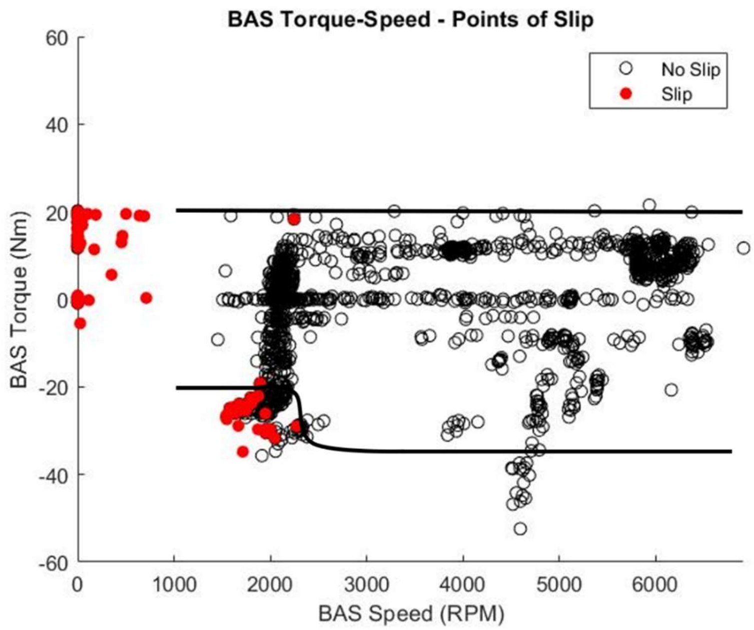


Figure 28: BAS Torque-Speed - Points of Slip

The results of the speed ratio analysis reaffirm the idea that belt slip was significantly more present when the BAS operated as a generator which is represented by the negative torque values seen in Figure 28. The presence of belt slip when the BAS operated as a motor was nearly completely due to the attempts to start the engine in test 4. The values where the BAS experienced slip near 0 Nm and 0 rpm are representative of belt slip that occurs when instantaneously starting the BAS from rest or instantaneously stopping the BAS. With the BAS acting as a generator, the cases where the speed ratio exceeded the deviation limits set were when the BAS was under torque demands of 20+ Nm while at low rpm. This provides a basis for controlling the BAS in that BAS low-speed torque demands should remain below 20 Nm if attempting to minimize the belt slip that occurs during operation. In general, the region bounded by the black lines in Figure 28 are a representation of the acceptable operating range for minimizing belt slip with the BAS. This is a starting point for the analysis but to gain a wholistic view on the acceptable operating ranges, additional testing would need to be completed to gather more data.

Chapter 5: Conclusions & Future Work

5.1. Conclusions

Creating a mounting solution called for careful consideration of spacing constraints, belt alignment, and the degree of tilt for the BAS system. A combination of CAD design as well as conventional measurement tools such as calipers and tape measures proved to be an effective method of designing said mount. In addition to this, the use of aluminum 6061-T6 for the construction of a BAS mount was found to be the best material in terms of the combination of strength, machinability, and cost.

Under engine idle conditions with the vehicle in drive, a BAS motor torque command of 15 Nm can be used to initiate acceleration in the vehicle by instantly providing enough torque to accelerate the engine speed before the engine itself begins to accelerate. If a vehicle is in engine idle condition with the vehicle being in neutral, applying any BAS motor torque command equal to or above 13 Nm will cause drastic spikes in current that are undesirable and could cause harm to the system. Therefore, all torque commands in these circumstances should be kept below 13 Nm to protect the electrical components in the system from failing. With the BAS acting as a generator and the engine under idle conditions, applying large impulse torque demands to the BAS will result in the stalling of the engine. Therefore, applying intermediate steps when attempting to demand larger torques from the BAS is necessary to prevent the engine stalling. In addition to this, applying torque demands greater than 25 Nm under these conditions results in the engine not being able to maintain idle speed. As a result, all torque demands should be kept beneath 25 Nm when the engine is under idle conditions to prevent any potential of the engine stalling.

Using the speed ratio allowed for insight into the presence of belt slip when subjecting the BAS – Engine system to various conditions. With the BAS acting as a motor and being subjected to step increases in torque up to 15 Nm, belt slip did not seem to occur when the engine is initially idling. This was the case for when the vehicle was in both neutral and drive. However, reducing the torque commanded from the BAS by a substantial amount (15+ Nm) instantaneously under the same operating conditions as above appears to result in minor belt slip. Therefore, one should avoid large instantaneous decreasing in the BAS torque command and instead take intermediate steps down to the desired value. In addition to this, the BAS system appears to experience belt slip when starting the engine. This may be an outcome that is unavoidable but additional tests should be conducted to provide more evidence for this theory.

With the BAS acting as a generator, belt slip appears to be more prevalent. This was made especially prevalent when analyzing the distribution and deviation of the speed ratio data. Under idle engine speed conditions with the vehicle in drive, the presence of belt slip appears to occur under BAS torque demands larger than 20 Nm. In addition to this, altering torque demands as the driver presses the accelerator seems to exacerbate the level of belt slip that occurs under idle engine speeds. As a result, BAS torque demands should be kept constant when the driver is attempting to accelerate from lower speeds. When the vehicle is maintaining higher speeds around 50 mph, the process of altering the BAS torque demand itself does not cause the onset of belt slip. However, torque demand values above 20 Nm results in the significant levels of belt slip with the slip being more consistent than the other operating conditions investigated. These conclusions were evident in both the independent test data as well as the additional belt slip analysis that was conducted. Therefore, BAS torque commands should reach a maximum of 20 Nm when reaching higher speeds to prevent belt slip from occurring and wearing out the belt.

As the implementation of BAS systems in automotive vehicles increase, so does the need for methods that allow for implementation of said BAS systems. In all, the methods outlined for this research provide a basis for the process of designing a mounting solution for a BAS as well as methods of analyzing the capabilities of said BAS system. The use of a speed ratio to anticipate where belt slip occurs provides a simple yet robust way to analyze the dynamics occurring between the engine and the BAS. In addition to this, finding various critical points of torque allows for greater insight into the useful range of the capabilities held by the BAS system.

5.2. Future Work

This research began to investigate the limitations and considerations that exist when mounting a BAS as well as operating a BAS. However, this is such an expansive topic that there are areas not touched by this research that could be investigated through further experiments and calculations. One area that has the ability for further research to be conducted is the process of designing a mounting solution for a BAS. Specifically, further research could be conducted into the maximum allowable degree of tilt for the BAS when mounted before issues would arise with the tensioning system for the BAS as well as what degree of tilt would optimize the performance of the BAS.

There are various areas that can be investigated in the future regarding the BAS as it operates as a motor. Applying torque commands while the vehicle is travelling at various driving speeds can provide insight into the usefulness of electric boost outside of initial acceleration. Analyzing these results can also provide further information regarding what conditions result in belt slip when using a BAS. More generally, conducting a wide range of tests with various speeds and BAS torque commands, then compiling and analyzing the resulting data would allow for analysis into the useful range of a BAS torque-speed curve. Certain regions of possible operation would be eliminated if there were either mechanical issues, electrical issues, or belt slip with said operation region in most operating conditions. This would allow for further development of the BAS torque-speed curve (Figure 28) to define a more wholistic view of the desired operating regions for the BAS.

Finally, developing a controls strategy for the BAS system is perhaps the most valuable future study for the implementation of BAS systems. Creating a controls strategy that avoids the undesirable system limits as well as the torque recommendations for various operating conditions posed by this research would be extremely useful. Having this controls strategy would allow for the BAS to avoid operating in undesirable regions. This controls strategy would need to be robust and somewhat modular in nature. A modular controls strategy is desired so that additional limitations on the desirable operating region of the BAS system found from future research could be easily implemented and altered. In addition to this, the controls strategy would also need logic that allows the BAS to properly implement start-stop technology. However, this would call for changes to the control logic for the engine as well. There are plans for this to occur in the near future.

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Appendix A: Test Data Plots for All Parameters

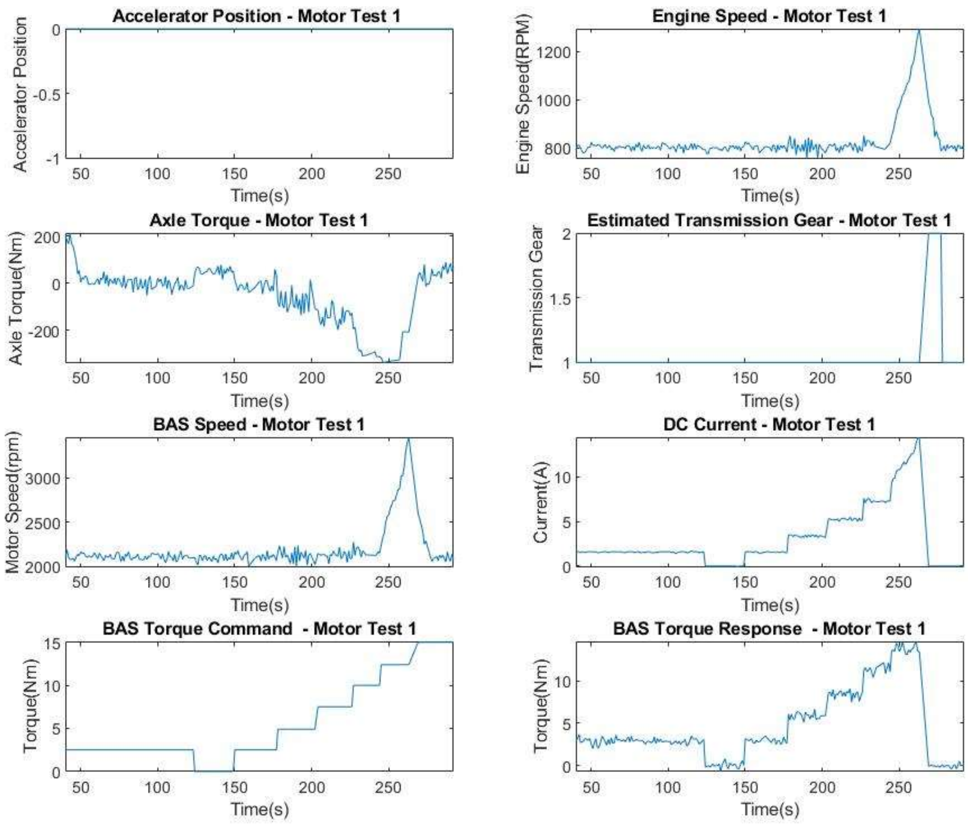

Figure 29: Test 1 - All Parameter Responses

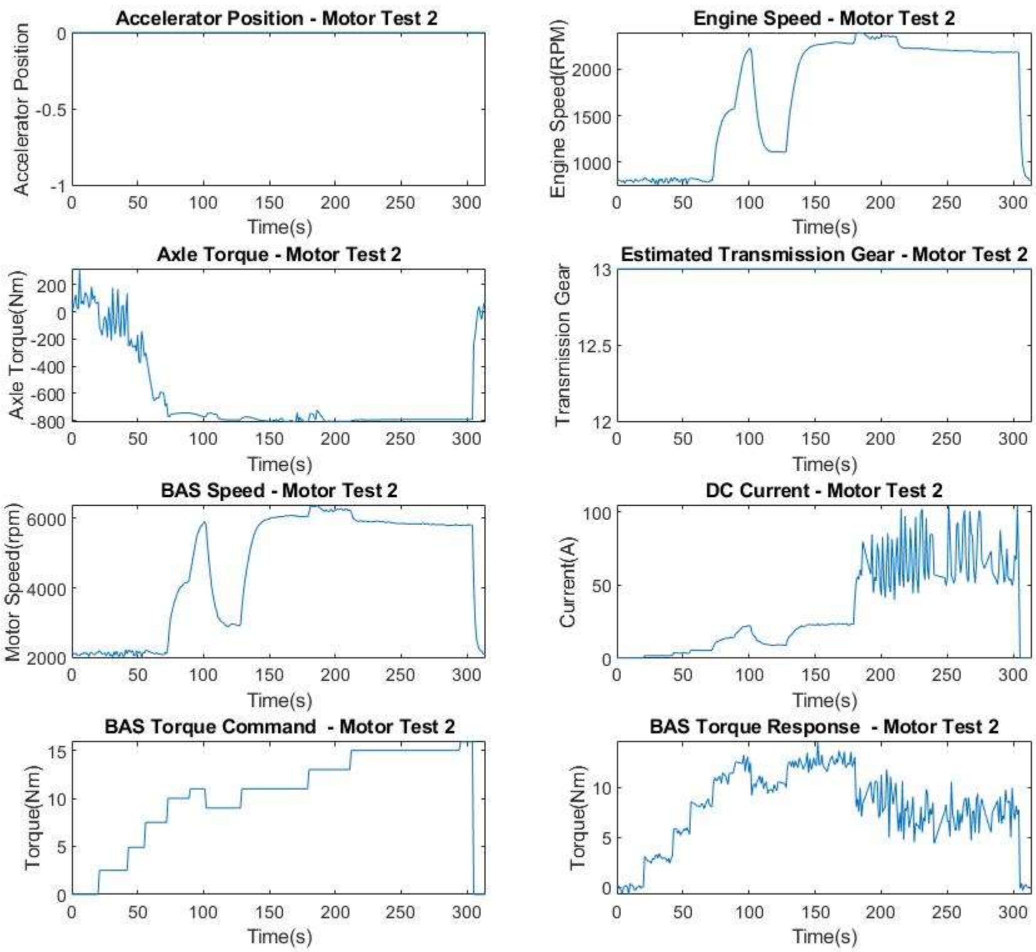

Figure 30: Test 2 - All Parameter Responses

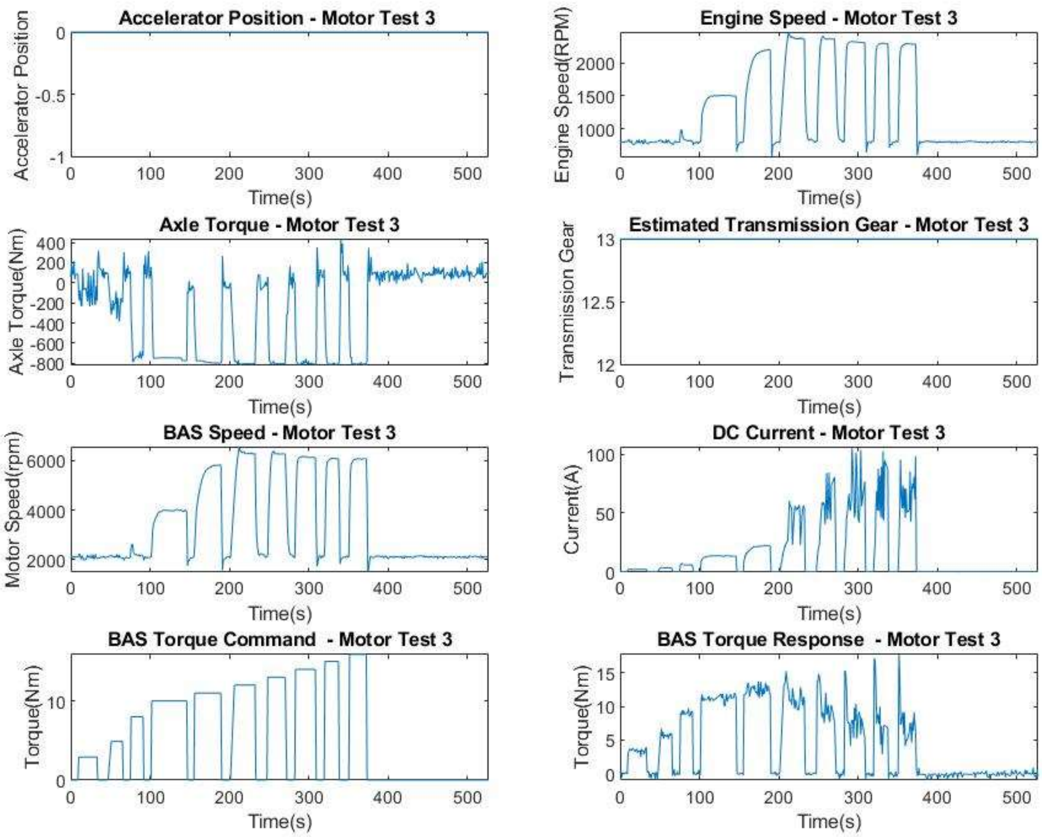

Figure 31: Test 3 - All Parameter Responses

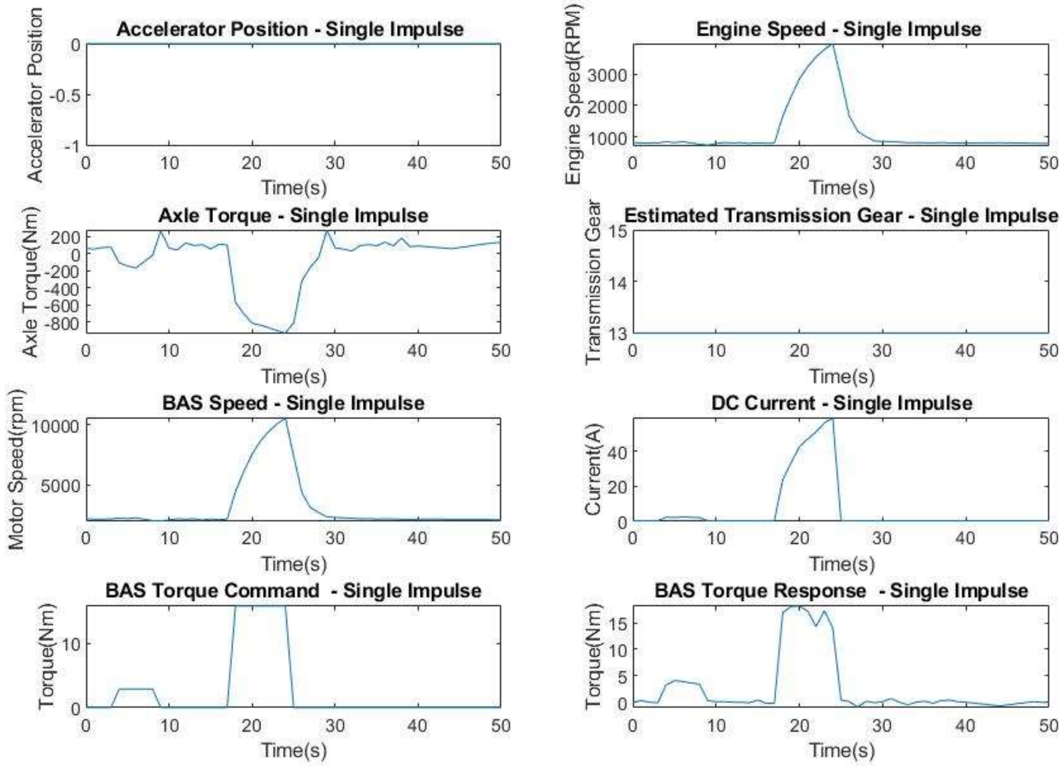

Figure 32: Single Impulse Test - All Parameter Responses

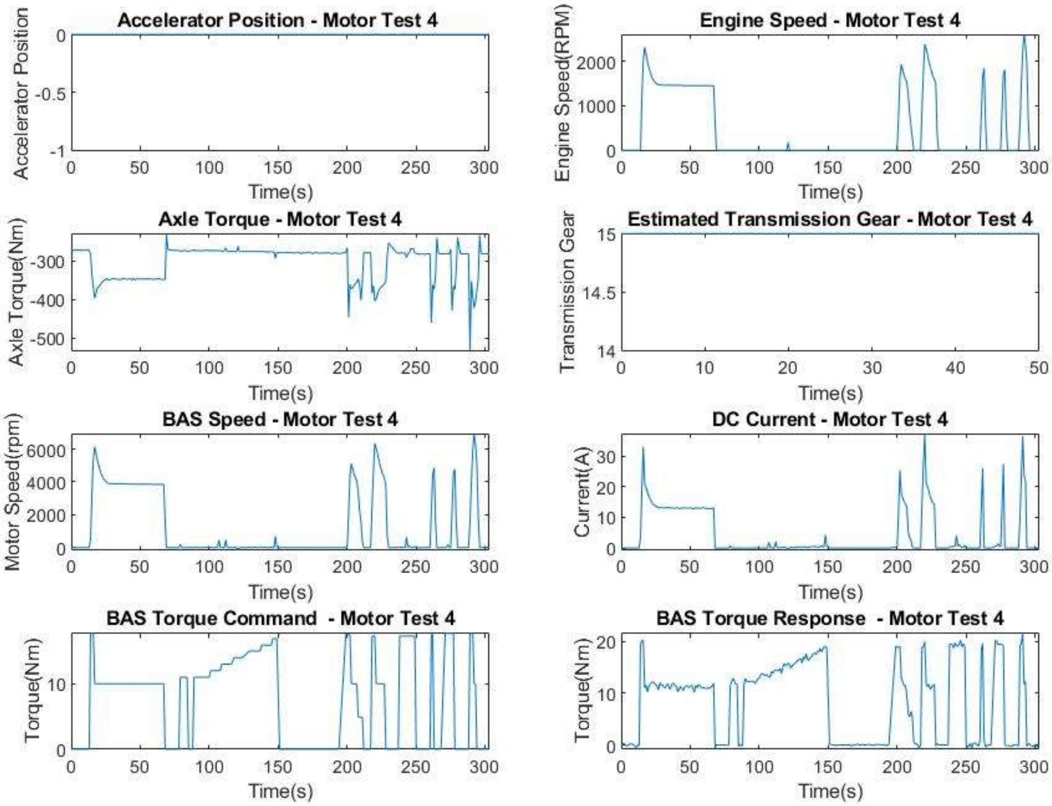

Figure 33: Test 4 - All Parameter Responses

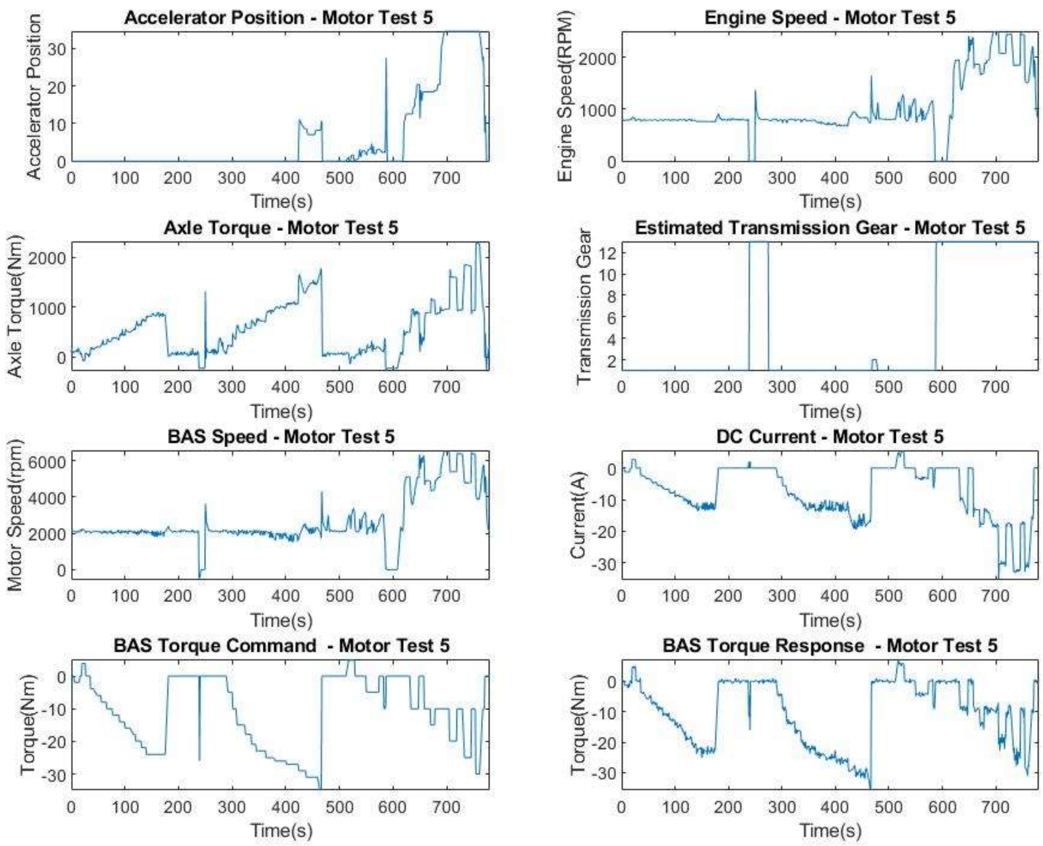

Figure 34: Test 5 - All Parameter Responses

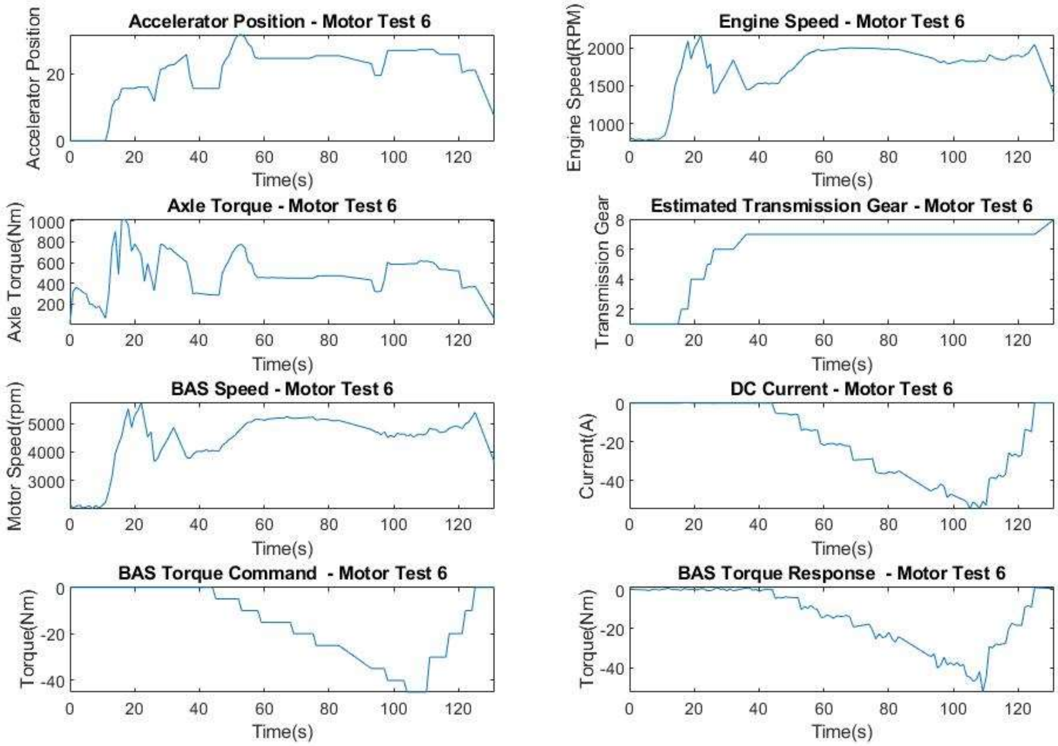

Figure 35: Test 6 - All Parameter Responses

Appendix B: Estimated Gear Description Table

Table 7: Estimated Gear Description

Estimated Gear Value	Actual Gear
1	1^{st} Gear
2	2^{nd} Gear
3	3^{rd} Gear
4	4^{th} Gear
5	5^{th} Gear
6	6^{th} Gear
7	7^{th} Gear
8	8^{th} Gear
9	9^{th} Gear
13	Neutral
15	Park

Appendix C: Matlab Code for Analysis

```
%% BAS Testing Data Processing - Ron Smith Thesis

clc
clear all
close all


%% Motor Test 1
% Engine on and drive

clc
clear all
close all
% Load in necessary test data
MTest1 = load("Motor1.mat");


%% Analyze Motor Test 1

% Filter out first 40 seconds - car in park during this
time (first
% 39 data points)
% Load time from data
t1 = MTest1.Ron_1.X.Data;
n1 = length(t1); % length of time vector
t1 = MTest1.Ron_1.X.Data(39:n1);



% Load various parameters recorded during test
AccPos1 = MTest1.Ron_1.Y(1).Data(39:n1); % [%]
EngSpd1 = MTest1.Ron_1.Y(2).Data(39:n1); % [rpm]
AxleTrq1 = MTest1.Ron_1.Y(3).Data(39:n1); % [Nm]
Transestgear1 = MTest1.Ron_1.Y(4).Data(39:n1);
D2Motorspeed1 = MTest1.Ron_1.Y(5).Data(39:n1); % [rpm]
DCBUSCurrent1 = MTest1.Ron_1.Y(6).Data(39:n1); % [A]
CommandedTorque1 = MTest1.Ron_1.Y(7).Data(39:n1); % [Nm]
TorqueFeedback1 = MTest1.Ron_1.Y(8).Data(39:n1); % [Nm]


% Graph parameters against time
Figure;
```

```
subplot(4,2,1)
plot(t1,AccPos1);title("Accelerator Position - Motor Test 1
");xlabel("Time(s)");ylabel("Accelerator
Position");axis([40 inf -inf inf]);
subplot(4,2,2)
plot(t1,EngSpd1);title("Engine Speed - Motor Test
1");xlabel("Time(s)");ylabel("Engine Speed(RPM)");axis([40
inf -inf inf]);
subplot(4,2,3)
plot(t1,AxleTrq1);title("Axle Torque - Motor Test
1");xlabel("Time(s)");ylabel("Axle Torque(Nm)");axis([40
inf -inf inf]);
subplot(4,2,4)
plot(t1,Transestgear1);title("Estimated Transmission Gear -
Motor Test 1");xlabel("Time(s)");ylabel("Transmission
Gear");axis([40 inf -inf inf]);
subplot(4,2,5)
plot(t1,D2Motorspeed1);title("BAS Speed - Motor Test
1");xlabel("Time(s)");ylabel("Motor Speed(rpm)");axis([40
inf -inf inf]);
subplot(4,2,6)
plot(t1,DCBUSCurrent1);title("DC Current - Motor Test
1");xlabel("Time(s)");ylabel("Current(A)");axis([40 inf -
inf inf]);
subplot(4,2,7)
plot(t1,CommandedTorque1);title("BAS Torque Command - Motor
Test 1");xlabel("Time(s)");ylabel("Torque(Nm)");axis([40
inf -inf inf]);
subplot(4,2,8)
plot(t1,TorqueFeedback1);title("BAS Torque Response - Motor
Test 1");xlabel("Time(s)");ylabel("Torque(Nm)");axis([40
inf -inf inf]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Test 1 Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Analysis of speed ratio for test 1
MSpd1 = double(D2Motorspeed1); % Convert from int16 to
double data type - needed for speed ratio calc
SR1 = MSpd1./EngSpd1; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
```

```
SR_f1 = filter(weight,1,SR1); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t1 = t1(5:length(t1));
SR_f1 = SR_f1(5:length(SR_f1));

% Set vector that will graph expected speed ratio
Base_SR1 = ones(1,length(SR_f1))*2.6382; % multiply by
baseline speed ratio

%graph speed ratio
Figure;
plot(t1,SR_f1,t1,Base_SR1)
title('Speed Ratio - Test 1')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')


%% Motor Test 2
% Engine on and neutral

clc
clear all
close all
% Load in necessary test data
MTest2 = load("Motor2.mat");


%% Analyze Motor Test 2

% Filter out first ____
% Load time from data
t2 = MTest2.Ron_2.X.Data;
n2 = length(t2); % length of time vector
t2 = MTest2.Ron_2.X.Data;



% Load various parameters recorded during test
```

```
AccPos2 = MTest2.Ron_2.Y(1).Data; % [%]
EngSpd2 = MTest2.Ron_2.Y(2).Data; % [rpm]
AxleTrq2 = MTest2.Ron_2.Y(3).Data; % [Nm]
Transestgear2 = MTest2.Ron_2.Y(4).Data;
D2Motorspeed2 = MTest2.Ron_2.Y(5).Data; % [rpm]
DCBUSCurrent2 = MTest2.Ron_2.Y(6).Data; % [A]
CommandedTorque2 = MTest2.Ron_2.Y(7).Data; % [Nm]
TorqueFeedback2 = MTest2.Ron_2.Y(8).Data; % [Nm]


% Graph parameters against time
Figure;
subplot(4,2,1)
plot(t2,AccPos2);title("Accelerator Position - Motor Test 2
");xlabel("Time(s)");ylabel("Accelerator Position");axis([-
inf inf -inf inf]);
subplot(4,2,2)
plot(t2,EngSpd2);title("Engine Speed - Motor Test
2");xlabel("Time(s)");ylabel("Engine Speed(RPM)");axis([-
inf inf -inf inf]);
subplot(4,2,3)
plot(t2,AxleTrq2);title("Axle Torque - Motor Test
2");xlabel("Time(s)");ylabel("Axle Torque(Nm)");axis([-inf
inf -inf inf]);
subplot(4,2,4)
plot(t2,Transestgear2);title("Estimated Transmission Gear -
Motor Test 2");xlabel("Time(s)");ylabel("Transmission
Gear");axis([-inf inf -inf inf]);
subplot(4,2,5)
plot(t2,D2Motorspeed2);title("BAS Speed - Motor Test
2");xlabel("Time(s)");ylabel("Motor Speed(rpm)");axis([-inf
inf -inf inf]);
subplot(4,2,6)
plot(t2,DCBUSCurrent2);title("DC Current - Motor Test
2");xlabel("Time(s)");ylabel("Current(A)");axis([-inf inf -
inf inf]);
subplot(4,2,7)
plot(t2,CommandedTorque2);title("BAS Torque Command - Motor
Test 2");xlabel("Time(s)");ylabel("Torque(Nm)");axis([-inf
inf -inf inf]);
subplot(4,2,8)
plot(t2,TorqueFeedback2);title("BAS Torque Response - Motor
Test 2");xlabel("Time(s)");ylabel("Torque(Nm)");axis([-inf
inf -inf inf]);
```

```
% Seperate plot for current excitation
Figure;
subplot(2,1,1)
plot(t2,DCBUSCurrent2);title("DC Current Spikes - Motor
Test 2");xlabel("Time(s)");ylabel("Current(A)");axis([170
inf -inf inf]);
subplot(2,1,2)
plot(t2,CommandedTorque2,t2,TorqueFeedback2);title("Torque
Responses - Motor Test
2");xlabel("Time(s)");ylabel("Torque(Nm)");axis([170 inf -
inf inf]);
legend('Torque Command','Torque Response')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Test 2 Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Analysis of speed ratio for test 2
MSpd2 = double(D2Motorspeed2); % Convert from int16 to
double data type - needed for speed ratio calc
SR2 = MSpd2./EngSpd2; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f2 = filter(weight,1,SR2); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t2 = t2(5:length(t2));
SR_f2 = SR_f2(5:length(SR_f2));

% Set vector that will graph expected speed ratio
Base_SR2 = ones(1,length(SR_f2))*2.6382; % multiply by
baseline speed ratio

% graph speed ratio
Figure;
plot(t2,SR_f2,t2,Base_SR2)
title('Speed Ratio - Test 2')
axis([-inf inf 2 3])
xlabel('Time(s)')
```

```
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')


%% Motor Test 3
% Engine on and neutral

clc
clear all
close all
% Load in necessary test data
MTest3 = load("Motor3.mat");


%% Analyze Motor Test 3

% Load time from data
t3 = MTest3.Ron_3.X.Data;
n3 = length(t3); % length of time vector
t3 = MTest3.Ron_3.X.Data;



% Load various parameters recorded during test
AccPos3 = MTest3.Ron_3.Y(1).Data; % [%]
EngSpd3 = MTest3.Ron_3.Y(2).Data; % [rpm]
AxleTrq3 = MTest3.Ron_3.Y(3).Data; % [Nm]
Transestgear3 = MTest3.Ron_3.Y(4).Data;
D2Motorspeed3 = MTest3.Ron_3.Y(5).Data; % [rpm]
DCBUSCurrent3 = MTest3.Ron_3.Y(6).Data; % [A]
CommandedTorque3 = MTest3.Ron_3.Y(7).Data; % [Nm]
TorqueFeedback3 = MTest3.Ron_3.Y(8).Data; % [Nm]


% Graph parameters against time
Figure;
subplot(4,2,1)
plot(t3,AccPos3);title("Accelerator Position - Motor Test 3
");xlabel("Time(s)");ylabel("Accelerator Position");axis([-
inf inf -inf inf]);
subplot(4,2,2)
plot(t3,EngSpd3);title("Engine Speed - Motor Test
3");xlabel("Time(s)");ylabel("Engine Speed(RPM)");axis([-
inf inf -inf inf]);
```

```
subplot(4,2,3)
plot(t3,AxleTrq3);title("Axle Torque - Motor Test
3");xlabel("Time(s)");ylabel("Axle Torque(Nm)");axis([-inf
inf -inf inf]);
subplot(4,2,4)
plot(t3,Transestgear3);title("Estimated Transmission Gear -
Motor Test 3");xlabel("Time(s)");ylabel("Transmission
Gear");axis([-inf inf -inf inf]);
subplot(4,2,5)
plot(t3,D2Motorspeed3);title("BAS Speed - Motor Test
3");xlabel("Time(s)");ylabel("Motor Speed(rpm)");axis([-inf
inf -inf inf]);
subplot(4,2,6)
plot(t3,DCBUSCurrent3);title("DC Current - Motor Test
3");xlabel("Time(s)");ylabel("Current(A)");axis([-inf inf -
inf inf]);
subplot(4,2,7)
plot(t3,CommandedTorque3);title("BAS Torque Command - Motor
Test 3");xlabel("Time(s)");ylabel("Torque(Nm)");axis([-inf
inf -inf inf]);
subplot(4,2,8)
plot(t3,TorqueFeedback3);title("BAS Torque Response - Motor
Test 3");xlabel("Time(s)");ylabel("Torque(Nm)");axis([-inf
inf -inf inf]);


% Seperate plot for current excitation
Figure;
subplot(2,1,1)
plot(t3,DCBUSCurrent3);title("DC Current Spikes - Motor
Test 3");xlabel("Time(s)");ylabel("Current(A)");axis([177
inf -inf inf]);
subplot(2,1,2)
plot(t3,CommandedTorque3,t3,TorqueFeedback3);title("Torque
Responses - Motor Test
3");xlabel("Time(s)");ylabel("Torque(Nm)");axis([177 inf -
inf inf]);
legend('Torque Command','Torque Response')


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Test 3 Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Analysis of speed ratio for test 4
```

```
MSpd3 = double(D2Motorspeed3); % Convert from int16 to
double data type - needed for speed ratio calc
SR3 = MSpd3./EngSpd3; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f3 = filter(weight,1,SR3); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t3 = t3(5:length(t3));
SR_f3 = SR_f3(5:length(SR_f3));

% Set vector that will graph expected speed ratio
Base_SR3 = ones(1,length(SR_f3))*2.6382; % multiply by
baseline speed ratio

%graph speed ratio
Figure;
plot(t3,SR_f3,t3,Base_SR3)
title('Speed Ratio - Test 3')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')


%% Motor Test 4
% Engine on and neutral

clc
clear all
close all
% Load in necessary test data
MTest4 = load("Motor4.mat");


%% Analyze Motor Test 4

% Load time from data
t4 = MTest4.Ron_4.X.Data;
n4 = length(t4); % length of time vector
```

```
t4 = MTest4.Ron_4.X.Data;


% Load various parameters recorded during test
AccPos4 = MTest4.Ron_4.Y(1).Data; % [%]
EngSpd4 = MTest4.Ron_4.Y(2).Data; % [rpm]
AxleTrq4 = MTest4.Ron_4.Y(3).Data; % [Nm]
Transestgear4 = MTest4.Ron_4.Y(4).Data;
D2Motorspeed4 = MTest4.Ron_4.Y(5).Data; % [rpm]
DCBUSCurrent4 = MTest4.Ron_4.Y(6).Data; % [A]
CommandedTorque4 = MTest4.Ron_4.Y(7).Data; % [Nm]
TorqueFeedback4 = MTest4.Ron_4.Y(8).Data; % [Nm]


% Graph parameters against time
Figure;
subplot(4,2,1)
plot(t4,AccPos4);title("Accelerator Position - Single
Impulse ");xlabel("Time(s)");ylabel("Accelerator
Position");axis([0 50 -inf inf]);
subplot(4,2,2)
plot(t4,EngSpd4);title("Engine Speed - Single Impulse
");xlabel("Time(s)");ylabel("Engine Speed(RPM)");axis([0 50
-inf inf]);
subplot(4,2,3)
plot(t4,AxleTrq4);title("Axle Torque - Single
Impulse");xlabel("Time(s)");ylabel("Axle
Torque(Nm)");axis([0 50 -inf inf]);
subplot(4,2,4)
plot(t4,Transestgear4);title("Estimated Transmission Gear -
Single Impulse");xlabel("Time(s)");ylabel("Transmission
Gear");axis([0 50 -inf inf]);
subplot(4,2,5)
plot(t4,D2Motorspeed4);title("BAS Speed - Single
Impulse");xlabel("Time(s)");ylabel("Motor
Speed(rpm)");axis([0 50 -inf inf]);
subplot(4,2,6)
plot(t4,DCBUSCurrent4);title("DC Current - Single
Impulse");xlabel("Time(s)");ylabel("Current(A)");axis([0 50
-inf inf]);
subplot(4,2,7)
plot(t4,CommandedTorque4);title("BAS Torque Command -
Single
```

```
Impulse");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 50
-inf inf]);
subplot(4,2,8)
plot(t4,TorqueFeedback4);title("BAS Torque Response -
Single
Impulse");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 50
-inf inf]);



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Test 4 Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Analysis of speed ratio for test 4
MSpd4 = double(D2Motorspeed4); % Convert from int16 to
double data type - needed for speed ratio calc
SR4 = MSpd4./EngSpd4; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f4 = filter(weight,1,SR4); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t4 = t4(5:length(t4));
SR_f4 = SR_f4(5:length(SR_f4));

% Set vector that will graph expected speed ratio
Base_SR4 = ones(1,length(SR_f4))*2.6382; % multiply by
baseline speed ratio

%graph speed ratio
Figure;
plot(t4,SR4(5:length(SR4)),t4,Base_SR4)
title('Speed Ratio - Test 4')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')


%% Motor Test 5
```

```
% Engine on and neutral

clc
clear all
close all
% Load in necessary test data
MTest5 = load("Motor5.mat");


%% Analyze Motor Test 5

% Load time from data
t5 = MTest5.Ron_6.X.Data;
n5 = length(t5); % length of time vector
t5 = MTest5.Ron_6.X.Data;



% Load various parameters recorded during test
AccPos5 = MTest5.Ron_6.Y(1).Data; % [%]
EngSpd5 = MTest5.Ron_6.Y(2).Data; % [rpm]
AxleTrq5 = MTest5.Ron_6.Y(3).Data; % [Nm]
Transestgear5 = MTest5.Ron_6.Y(4).Data;
D2Motorspeed5 = MTest5.Ron_6.Y(5).Data; % [rpm]
DCBUSCurrent5 = MTest5.Ron_6.Y(6).Data; % [A]
CommandedTorque5 = MTest5.Ron_6.Y(7).Data; % [Nm]
TorqueFeedback5 = MTest5.Ron_6.Y(8).Data; % [Nm]


% Graph parameters against time
Figure;
subplot(4,2,1)
plot(t5,AccPos5);title("Accelerator Position - Motor Test 4
");xlabel("Time(s)");ylabel("Accelerator Position");axis([0
inf -inf inf]);
subplot(4,2,2)
plot(t5,EngSpd5);title("Engine Speed - Motor Test
4");xlabel("Time(s)");ylabel("Engine Speed(RPM)");axis([0
inf -inf inf]);
subplot(4,2,3)
plot(t5,AxleTrq5);title("Axle Torque - Motor Test
4");xlabel("Time(s)");ylabel("Axle Torque(Nm)");axis([0 inf
-inf inf]);
subplot(4,2,4)
```

```
plot(t5,Transestgear5);title("Estimated Transmission Gear -
Motor Test 4");xlabel("Time(s)");ylabel("Transmission
Gear");axis([0 50 -inf inf]);
subplot(4,2,5)
plot(t5,D2Motorspeed5);title("BAS Speed - Motor Test
4");xlabel("Time(s)");ylabel("Motor Speed(rpm)");axis([0
inf -inf inf]);
subplot(4,2,6)
plot(t5,DCBUSCurrent5);title("DC Current - Motor Test
4");xlabel("Time(s)");ylabel("Current(A)");axis([0 inf -inf
inf]);
subplot(4,2,7)
plot(t5,CommandedTorque5);title("BAS Torque Command - Motor
Test 4");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf
-inf inf]);
subplot(4,2,8)
plot(t5,TorqueFeedback5);title("BAS Torque Response - Motor
Test 4");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf
-inf inf]);


%% Motor Test 6
% Engine on and neutral
% Regen Test 1

clc
clear all
close all
% Load in necessary test data
MTest6 = load("Regen1.mat");


%% Analyze Motor Test 6

% Load time from data
t6 = MTest6.Ron_6.X.Data;
n6 = length(t6); % length of time vector
t6 = MTest6.Ron_6.X.Data;



% Load various parameters recorded during test
AccPos6 = MTest6.Ron_6.Y(1).Data; % [%]
EngSpd6 = MTest6.Ron_6.Y(2).Data; % [rpm]
```

```
AxleTrq6 = MTest6.Ron_6.Y(3).Data; % [Nm]
Transestgear6 = MTest6.Ron_6.Y(4).Data;
D2Motorspeed6 = MTest6.Ron_6.Y(5).Data; % [rpm]
DCBUSCurrent6 = MTest6.Ron_6.Y(6).Data; % [A]
CommandedTorque6 = MTest6.Ron_6.Y(7).Data; % [Nm]
TorqueFeedback6 = MTest6.Ron_6.Y(8).Data; % [Nm]


% Graph parameters against time
Figure;
subplot(4,2,1)
plot(t6,AccPos6);title("Accelerator Position - Motor Test 5
");xlabel("Time(s)");ylabel("Accelerator Position");axis([0
inf -inf inf]);
subplot(4,2,2)
plot(t6,EngSpd6);title("Engine Speed - Motor Test
5");xlabel("Time(s)");ylabel("Engine Speed(RPM)");axis([0
inf -inf inf]);
subplot(4,2,3)
plot(t6,AxleTrq6);title("Axle Torque - Motor Test
5");xlabel("Time(s)");ylabel("Axle Torque(Nm)");axis([0 inf
-inf inf]);
subplot(4,2,4)
plot(t6,Transestgear6);title("Estimated Transmission Gear -
Motor Test 5");xlabel("Time(s)");ylabel("Transmission
Gear");axis([0 inf -inf inf]);
subplot(4,2,5)
plot(t6,D2Motorspeed6);title("BAS Speed - Motor Test
5");xlabel("Time(s)");ylabel("Motor Speed(rpm)");axis([0
inf -inf inf]);
subplot(4,2,6)
plot(t6,DCBUSCurrent6);title("DC Current - Motor Test
5");xlabel("Time(s)");ylabel("Current(A)");axis([0 inf -inf
inf]);
subplot(4,2,7)
plot(t6,CommandedTorque6);title("BAS Torque Command - Motor
Test 5");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf
-inf inf]);
subplot(4,2,8)
plot(t6,TorqueFeedback6);title("BAS Torque Response - Motor
Test 5");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf
-inf inf]);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Test 6 Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Analysis of speed ratio for test 6
MSpd6 = double(D2Motorspeed6); % Convert from int16 to
double data type - needed for speed ratio calc
SR6 = MSpd6./EngSpd6; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f6 = filter(weight,1,SR6); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t6 = t6(5:length(t6));
SR_f6 = SR_f6(5:length(SR_f6));

% Set vector that will graph expected speed ratio
Base_SR6 = ones(1,length(SR_f6))*2.6382; % multiply by
baseline speed ratio

%graph speed ratio
Figure;
plot(t6,SR_f6,t6,Base_SR6)
title('Speed Ratio - Test 5')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')


%% Motor Test 7
% Engine on and neutral
% Regen Test 2

clc
clear all
close all
% Load in necessary test data
MTest7 = load("Regen2.mat");
```

```
%% Analyze Motor Test 7

% Load time from data
t7 = MTest7.Ron_7.X.Data;
n7 = length(t7); % length of time vector
t7 = MTest7.Ron_7.X.Data;



% Load various parameters recorded during test
AccPos7 = MTest7.Ron_7.Y(1).Data; % [%]
EngSpd7 = MTest7.Ron_7.Y(2).Data; % [rpm]
AxleTrq7 = MTest7.Ron_7.Y(3).Data; % [Nm]
Transestgear7 = MTest7.Ron_7.Y(4).Data;
D2Motorspeed7 = MTest7.Ron_7.Y(5).Data; % [rpm]
DCBUSCurrent7 = MTest7.Ron_7.Y(6).Data; % [A]
CommandedTorque7 = MTest7.Ron_7.Y(7).Data; % [Nm]
TorqueFeedback7 = MTest7.Ron_7.Y(8).Data; % [Nm]


% Graph parameters against time
Figure;
subplot(4,2,1)
plot(t7,AccPos7);title("Accelerator Position - Motor Test 6
");xlabel("Time(s)");ylabel("Accelerator Position");axis([0
inf -inf inf]);
subplot(4,2,2)
plot(t7,EngSpd7);title("Engine Speed - Motor Test
6");xlabel("Time(s)");ylabel("Engine Speed(RPM)");axis([0
inf -inf inf]);
subplot(4,2,3)
plot(t7,AxleTrq7);title("Axle Torque - Motor Test
6");xlabel("Time(s)");ylabel("Axle Torque(Nm)");axis([0 inf
-inf inf]);
subplot(4,2,4)
plot(t7,Transestgear7);title("Estimated Transmission Gear -
Motor Test 6");xlabel("Time(s)");ylabel("Transmission
Gear");axis([0 inf -inf inf]);
subplot(4,2,5)
plot(t7,D2Motorspeed7);title("BAS Speed - Motor Test
6");xlabel("Time(s)");ylabel("Motor Speed(rpm)");axis([0
inf -inf inf]);
subplot(4,2,6)
```

```
plot(t7,DCBUSCurrent7);title("DC Current - Motor Test
6");xlabel("Time(s)");ylabel("Current(A)");axis([0 inf -inf
inf]);
subplot(4,2,7)
plot(t7,CommandedTorque7);title("BAS Torque Command - Motor
Test 6");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf
-inf inf]);
subplot(4,2,8)
plot(t7,TorqueFeedback7);title("BAS Torque Response - Motor
Test 6");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf
-inf inf]);



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Test 7 Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Analysis of speed ratio for test 7
MSpd7 = double(D2Motorspeed7); % Convert from int16 to
double data type - needed for speed ratio calc
SR7 = MSpd7./EngSpd7; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f7 = filter(weight,1,SR7); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t7 = t7(5:length(t7));
SR_f7 = SR_f7(5:length(SR_f7));

% Set vector that will graph expected speed ratio
Base_SR7 = ones(1,length(SR_f7))*2.6382; % multiply by
baseline speed ratio

%graph speed ratio
Figure;
plot(t7,SR_f7,t7,Base_SR7)
title('Speed Ratio - Test 6')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
```

```
legend('Experiment Speed Ratio','Baseline Speed Ratio')

%% Sepcific Analysis for Certain Characteristics of BAS
Response


clc
clear all
close all

% Load all test cases for easy access for any following
Section
MTest1 = load("Motor1.mat");
MTest2 = load("Motor2.mat");
MTest3 = load("Motor3.mat");
MTest4 = load("Motor4.mat");
MTest5 = load("Motor5.mat");
MTest6 = load("Regen1.mat");
MTest7 = load("Regen2.mat");


% Load Basic parameters for each test case
% Filter out first 40 seconds - car in park during this
time (first
% 39 data points)
% Load time from data
t1 = MTest1.Ron_1.X.Data;
n1 = length(t1); % length of time vector
t1 = MTest1.Ron_1.X.Data(39:n1);

% Filter out first ____
% Load time from data
t2 = MTest2.Ron_2.X.Data;
n2 = length(t2); % length of time vector

% Load time from data
t3 = MTest3.Ron_3.X.Data;
n3 = length(t3); % length of time vector

% Load time from data
t4 = MTest4.Ron_4.X.Data;
n4 = length(t4); % length of time vector
```

```
% Load time from data
t5 = MTest5.Ron_6.X.Data;
n5 = length(t5); % length of time vector

% Load time from data
t6 = MTest6.Ron_6.X.Data;
n6 = length(t6); % length of time vector

% Load time from data
t7 = MTest7.Ron_7.X.Data;
n7 = length(t7); % length of time vector


%% BAS RPM vs Engine RPM - Speed Ratio - From Test 1

D2Motorspeed1 = MTest1.Ron_1.Y(5).Data(39:n1); % [rpm]
DoubleMotorspeed1 = double(D2Motorspeed1); % Convert from
int16 to double data type - needed for speed ratio calc
EngSpd1 = MTest1.Ron_1.Y(2).Data(39:n1); % [rpm]
CommandedTorque1 = MTest1.Ron_1.Y(7).Data(39:n1); % [Nm]
TorqueFeedback1 = MTest1.Ron_1.Y(8).Data(39:n1); % [Nm]


% graph displaying time vs BAS torque commanded
Figure;
subplot(2,1,1)
plot(t1,CommandedTorque1,t1,TorqueFeedback1)
axis([40 inf -inf inf])
title(" BAS Torque Command - Idle")
xlabel("Time (s)")
ylabel("Torque (Nm)")
legend("Commanded Torque", "Torque
Feedback",'location',"northwest")

% Comparing BAS and engine rpm
subplot(2,1,2)
plot(t1,D2Motorspeed1,t1,EngSpd1)
axis([40 inf -inf inf])
title(" BAS Speed vs Engine Speed - Idle")
xlabel("Time (s)")
ylabel("Speed (RPM)")
legend("BAS Speed","Engine Speed",'location','northwest')
```

```
% Calculate speed ratio that will be used to determine belt
slip in other
% cases
speedratio = mean(DoubleMotorspeed1(1:67)./EngSpd1(1:67));

% Practice for filtering data to create cleaner graphs
% % % % % coeff = ones(1,5)/5;
% % % % % avgrpm5 = filter(coeff,1,D2Motorspeed1);
% % % % % Figure;
% % % % % plot(t1,D2Motorspeed1, t1,avgrpm5)

%% Create single graph that has all motor speed ratios and
torque commands
% Load various parameters recorded during test

EngSpd1 = MTest1.Ron_1.Y(2).Data(39:n1); % [rpm]
Transestgear1 = MTest1.Ron_1.Y(4).Data(39:n1);
D2Motorspeed1 = MTest1.Ron_1.Y(5).Data(39:n1); % [rpm]
DCBUSCurrent1 = MTest1.Ron_1.Y(6).Data(39:n1); % [A]
CommandedTorque1 = MTest1.Ron_1.Y(7).Data(39:n1); % [Nm]
TorqueFeedback1 = MTest1.Ron_1.Y(8).Data(39:n1); % [Nm]

% Load various parameters recorded during test
AccPos2 = MTest2.Ron_2.Y(1).Data; % [%]
EngSpd2 = MTest2.Ron_2.Y(2).Data; % [rpm]
AxleTrq2 = MTest2.Ron_2.Y(3).Data; % [Nm]
Transestgear2 = MTest2.Ron_2.Y(4).Data;
D2Motorspeed2 = MTest2.Ron_2.Y(5).Data; % [rpm]
DCBUSCurrent2 = MTest2.Ron_2.Y(6).Data; % [A]
CommandedTorque2 = MTest2.Ron_2.Y(7).Data; % [Nm]
TorqueFeedback2 = MTest2.Ron_2.Y(8).Data; % [Nm]

% Load various parameters recorded during test
AccPos3 = MTest3.Ron_3.Y(1).Data; % [%]
EngSpd3 = MTest3.Ron_3.Y(2).Data; % [rpm]
AxleTrq3 = MTest3.Ron_3.Y(3).Data; % [Nm]
Transestgear3 = MTest3.Ron_3.Y(4).Data;
D2Motorspeed3 = MTest3.Ron_3.Y(5).Data; % [rpm]
DCBUSCurrent3 = MTest3.Ron_3.Y(6).Data; % [A]
CommandedTorque3 = MTest3.Ron_3.Y(7).Data; % [Nm]
TorqueFeedback3 = MTest3.Ron_3.Y(8).Data; % [Nm]

% Load various parameters recorded during test
AccPos6 = MTest6.Ron_6.Y(1).Data; % [%]
```

```
EngSpd6 = MTest6.Ron_6.Y(2).Data; % [rpm]
AxleTrq6 = MTest6.Ron_6.Y(3).Data; % [Nm]
Transestgear6 = MTest6.Ron_6.Y(4).Data;
D2Motorspeed6 = MTest6.Ron_6.Y(5).Data; % [rpm]
DCBUSCurrent6 = MTest6.Ron_6.Y(6).Data; % [A]
CommandedTorque6 = MTest6.Ron_6.Y(7).Data; % [Nm]
TorqueFeedback6 = MTest6.Ron_6.Y(8).Data; % [Nm]

% Load various parameters recorded during test
AccPos7 = MTest7.Ron_7.Y(1).Data; % [%]
EngSpd7 = MTest7.Ron_7.Y(2).Data; % [rpm]
AxleTrq7 = MTest7.Ron_7.Y(3).Data; % [Nm]
Transestgear7 = MTest7.Ron_7.Y(4).Data;
D2Motorspeed7 = MTest7.Ron_7.Y(5).Data; % [rpm]
DCBUSCurrent7 = MTest7.Ron_7.Y(6).Data; % [A]
CommandedTorque7 = MTest7.Ron_7.Y(7).Data; % [Nm]
TorqueFeedback7 = MTest7.Ron_7.Y(8).Data; % [Nm]


Figure;
subplot(3,2,1)
plot(t1,SR_f1,t1,Base_SR1)
title('Speed Ratio - Test 1')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')
subplot(3,2,2)
plot(t1,CommandedTorque1(5:end))
title("BAS Torque Command - Motor Test
1");xlabel("Time(s)");ylabel("Torque(Nm)");axis([40 inf -
inf inf]);

subplot(3,2,3)
plot(t2,SR_f2,t2,Base_SR2)
title('Speed Ratio - Test 2')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')
subplot(3,2,4)
plot(t2,CommandedTorque2(5:end))
```

```
title("BAS Torque Command - Motor Test
2");xlabel("Time(s)");ylabel("Torque(Nm)");axis([-inf inf -
inf inf]);

subplot(3,2,5)
plot(t3,SR_f3,t3,Base_SR3)
title('Speed Ratio - Test 3')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')
subplot(3,2,6)
plot(t3,CommandedTorque3(5:end))
title("BAS Torque Command - Motor Test
3");xlabel("Time(s)");ylabel("Torque(Nm)");axis([-inf inf -
inf inf]);


%% Test 5 & 6 speed ratio plots with torque demand plots

Figure;

subplot(2,2,1)
plot(t6(1:435),SR_f6(1:435),t6(1:435),Base_SR6(1:435))
title('Speed Ratio - Test 5')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')
subplot(2,2,2)
plot(t6(1:435),CommandedTorque6(5:439))
title("BAS Torque Command - Motor Test
5");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf -inf
inf]);

subplot(2,2,3)
plot(t7,SR_f7,t7,Base_SR7)
title('Speed Ratio - Test 6')
axis([-inf inf 2 3])
xlabel('Time(s)')
ylabel('Speed Ratio (RPM/RPM)')
legend('Experiment Speed Ratio','Baseline Speed Ratio')
subplot(2,2,4)
plot(t7,CommandedTorque7(5:end))
```

```
title("BAS Torque Command - Motor Test
6");xlabel("Time(s)");ylabel("Torque(Nm)");axis([0 inf -inf
inf]);
```

```
%% Speed Ratio Data load

clc
clear all
close all

%% Load in data

% Load all test cases for easy access for any following
Section
MTest1 = load("Motor1.mat");
MTest2 = load("Motor2.mat");
MTest3 = load("Motor3.mat");
MTest4 = load("Motor4.mat");
MTest5 = load("Motor5.mat");
MTest6 = load("Regen1.mat");
MTest7 = load("Regen2.mat");


% Load Basic parameters for each test case
% Filter out first 40 seconds - car in park during this
time (first
% 39 data points)
% Load time from data
t1 = MTest1.Ron_1.X.Data;
n1 = length(t1); % length of time vector
t1 = MTest1.Ron_1.X.Data(39:n1);

% Filter out first ____
% Load time from data
t2 = MTest2.Ron_2.X.Data;
n2 = length(t2); % length of time vector

% Load time from data
t3 = MTest3.Ron_3.X.Data;
n3 = length(t3); % length of time vector

% Load time from data
t4 = MTest4.Ron_4.X.Data;
n4 = length(t4); % length of time vector

% Load time from data
t5 = MTest5.Ron_6.X.Data;
n5 = length(t5); % length of time vector
```

```
% Load time from data
t6 = MTest6.Ron_6.X.Data;
n6 = length(t6); % length of time vector

% Load time from data
t7 = MTest7.Ron_7.X.Data;
n7 = length(t7); % length of time vector


%% Set variables for data

EngSpd1 = MTest1.Ron_1.Y(2).Data(39:n1); % [rpm]
Transestgear1 = MTest1.Ron_1.Y(4).Data(39:n1);
D2Motorspeed1 = MTest1.Ron_1.Y(5).Data(39:n1); % [rpm]
DCBUSCurrent1 = MTest1.Ron_1.Y(6).Data(39:n1); % [A]
CommandedTorque1 = MTest1.Ron_1.Y(7).Data(39:n1); % [Nm]
TorqueFeedback1 = MTest1.Ron_1.Y(8).Data(39:n1); % [Nm]

% Load various parameters recorded during test
AccPos2 = MTest2.Ron_2.Y(1).Data; % [%]
EngSpd2 = MTest2.Ron_2.Y(2).Data; % [rpm]
AxleTrq2 = MTest2.Ron_2.Y(3).Data; % [Nm]
Transestgear2 = MTest2.Ron_2.Y(4).Data;
D2Motorspeed2 = MTest2.Ron_2.Y(5).Data; % [rpm]
DCBUSCurrent2 = MTest2.Ron_2.Y(6).Data; % [A]
CommandedTorque2 = MTest2.Ron_2.Y(7).Data; % [Nm]
TorqueFeedback2 = MTest2.Ron_2.Y(8).Data; % [Nm]

% Load various parameters recorded during test
AccPos3 = MTest3.Ron_3.Y(1).Data; % [%]
EngSpd3 = MTest3.Ron_3.Y(2).Data; % [rpm]
AxleTrq3 = MTest3.Ron_3.Y(3).Data; % [Nm]
Transestgear3 = MTest3.Ron_3.Y(4).Data;
D2Motorspeed3 = MTest3.Ron_3.Y(5).Data; % [rpm]
DCBUSCurrent3 = MTest3.Ron_3.Y(6).Data; % [A]
CommandedTorque3 = MTest3.Ron_3.Y(7).Data; % [Nm]
TorqueFeedback3 = MTest3.Ron_3.Y(8).Data; % [Nm]

% Load various parameters recorded during test
AccPos5 = MTest5.Ron_6.Y(1).Data; % [%]
EngSpd5 = MTest5.Ron_6.Y(2).Data; % [rpm]
AxleTrq5 = MTest5.Ron_6.Y(3).Data; % [Nm]
Transestgear5 = MTest5.Ron_6.Y(4).Data;
```

```
D2Motorspeed5 = MTest5.Ron_6.Y(5).Data; % [rpm]
DCBUSCurrent5 = MTest5.Ron_6.Y(6).Data; % [A]
CommandedTorque5 = MTest5.Ron_6.Y(7).Data; % [Nm]
TorqueFeedback5 = MTest5.Ron_6.Y(8).Data; % [Nm]

% Load various parameters recorded during test
AccPos6 = MTest6.Ron_6.Y(1).Data; % [%]
EngSpd6 = MTest6.Ron_6.Y(2).Data; % [rpm]
AxleTrq6 = MTest6.Ron_6.Y(3).Data; % [Nm]
Transestgear6 = MTest6.Ron_6.Y(4).Data;
D2Motorspeed6 = MTest6.Ron_6.Y(5).Data; % [rpm]
DCBUSCurrent6 = MTest6.Ron_6.Y(6).Data; % [A]
CommandedTorque6 = MTest6.Ron_6.Y(7).Data; % [Nm]
TorqueFeedback6 = MTest6.Ron_6.Y(8).Data; % [Nm]

% Load various parameters recorded during test
AccPos7 = MTest7.Ron_7.Y(1).Data; % [%]
EngSpd7 = MTest7.Ron_7.Y(2).Data; % [rpm]
AxleTrq7 = MTest7.Ron_7.Y(3).Data; % [Nm]
Transestgear7 = MTest7.Ron_7.Y(4).Data;
D2Motorspeed7 = MTest7.Ron_7.Y(5).Data; % [rpm]
DCBUSCurrent7 = MTest7.Ron_7.Y(6).Data; % [A]
CommandedTorque7 = MTest7.Ron_7.Y(7).Data; % [Nm]
TorqueFeedback7 = MTest7.Ron_7.Y(8).Data; % [Nm]

%% Calculate speed ratios


% Analysis of speed ratio for test 7
MSpd7 = double(D2Motorspeed7); % Convert from int16 to
double data type - needed for speed ratio calc
SR7 = MSpd7./EngSpd7; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f7 = filter(weight,1,SR7); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t7 = t7(5:length(t7));
SR_f7 = SR_f7(5:length(SR_f7));
```

```
% Analysis of speed ratio for test 6
MSpd6 = double(D2Motorspeed6); % Convert from int16 to
double data type - needed for speed ratio calc
SR6 = MSpd6./EngSpd6; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f6 = filter(weight,1,SR6); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t6 = t6(5:length(t6));
SR_f6 = SR_f6(5:length(SR_f6));

% Analysis of speed ratio for test 4
MSpd3 = double(D2Motorspeed3); % Convert from int16 to
double data type - needed for speed ratio calc
SR3 = MSpd3./EngSpd3; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f3 = filter(weight,1,SR3); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t3 = t3(5:length(t3));
SR_f3 = SR_f3(5:length(SR_f3));

% Analysis of speed ratio for test 2
MSpd2 = double(D2Motorspeed2); % Convert from int16 to
double data type - needed for speed ratio calc
SR2 = MSpd2./EngSpd2; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f2 = filter(weight,1,SR2); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
```

```
% filter
t2 = t2(5:length(t2));
SR_f2 = SR_f2(5:length(SR_f2));

% Analysis of speed ratio for test 1
MSpd1 = double(D2Motorspeed1); % Convert from int16 to
double data type - needed for speed ratio calc
SR1 = MSpd1./EngSpd1; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f1 = filter(weight,1,SR1); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t1 = t1(5:length(t1));
SR_f1 = SR_f1(5:length(SR_f1));

% Calculate speed ratio that will be used to determine belt
slip in other
% cases
baselinespeedratio = mean(MSpd1(1:67)./EngSpd1(1:67));


% Analysis of speed ratio for test 2
MSpd5 = double(D2Motorspeed5); % Convert from int16 to
double data type - needed for speed ratio calc
SR5 = MSpd5./EngSpd5; % calculate speed ratio

%filter data to get better approximation of extreme values
weight = ones(1,5)/5;
SR_f5 = filter(weight,1,SR5); % moving average filter with
N = 5

% Take out first 5 data points of filtered data to
eliminate delay caused
% filter
t5 = t5(5:length(t5));
SR_f5 = SR_f5(5:length(SR_f5));
```

```
%% Speed Ratio Trend analysis

% Run script that loads data
SR_data;

% Create variable to add together all of the speed ratios
Net_SR = [SR1 SR2 SR3 SR5 SR6 SR7];

% Index out all infinite from Net values
index = Net_SR == Inf;
Net_SR = Net_SR(index==0);
index = Net_SR == -Inf;
Net_SR = Net_SR(index==0);


% Create Histogram for Speed Ratios of Tests 1, 2, 3, 6, 7

Figure;
histogram(Net_SR)
title('Speed Ratio Distribution')
axis([1.5 4.5 -inf inf])
xlabel('Speed Ratio (RPM/RPM)')
ylabel('# of Data Points')


% Calculate standard deviation for speed ratio
dev = std(Net_SR,'omitnan');
mean = mean(Net_SR,'omitnan');

%% Organize potential belt slip opportunities

% Use for loops and if loops to sift through data for each
test to isolate
% values that are greater than 2 standard deviations from
mean
upper = 2*dev+mean; % upper deviation limit
lower = -2*dev+mean; % lower deviation limit

% Set variable to use to expand matrices as new values
occur
ind = 1;


% Test 1 data analysis
for i = 1:length(SR1)
```

```
  if SR1(i) > upper || SR1(i) < lower % if outside of
deviation limits

    slip_Torque(ind) = TorqueFeedback1(i); % Torque read
from BAS
    slip_Speed(ind) = D2Motorspeed1(i); % Speed read from
BAS
    ind = ind+1; % increase indexing variable

  else
    Op_Torque(ind) = TorqueFeedback1(i); % Torque read from
BAS
    Op_Speed(ind) = D2Motorspeed1(i); % Speed read from BAS
    ind = ind+1; % increase indexing variable

  end
end

% Test 2 data analysis
for i = 1:length(SR2)

  if SR2(i) > upper || SR2(i) < lower % if outside of
deviation limits

    slip_Torque(ind) = TorqueFeedback2(i); % Torque read
from BAS
    slip_Speed(ind) = D2Motorspeed2(i); % Speed read from
BAS
    ind = ind+1; % increase indexing variable

  else
    Op_Torque(ind) = TorqueFeedback2(i); % Torque read from
BAS
    Op_Speed(ind) = D2Motorspeed2(i); % Speed read from BAS
    ind = ind+1; % increase indexing variable

  end
end

% Test 3 data analysis
for i = 1:length(SR3)
```

```
  if SR3(i) > upper || SR3(i) < lower % if outside of
deviation limits

    slip_Torque(ind) = TorqueFeedback3(i); % Torque read
from BAS
    slip_Speed(ind) = D2Motorspeed3(i); % Speed read from
BAS
    ind = ind+1; % increase indexing variable

  else
    Op_Torque(ind) = TorqueFeedback3(i); % Torque read from
BAS
    Op_Speed(ind) = D2Motorspeed3(i); % Speed read from BAS
    ind = ind+1; % increase indexing variable

  end
end

% Test 5 data analysis
for i = 1:length(SR5)

  if SR5(i) > upper || SR5(i) < lower % if outside of
deviation limits

    slip_Torque(ind) = TorqueFeedback5(i); % Torque read
from BAS
    slip_Speed(ind) = D2Motorspeed5(i); % Speed read from
BAS
    ind = ind+1; % increase indexing variable

  else
    Op_Torque(ind) = TorqueFeedback5(i); % Torque read from
BAS
    Op_Speed(ind) = D2Motorspeed5(i); % Speed read from BAS
    ind = ind+1; % increase indexing variable

  end
end

% Test 6 data analysis
for i = 1:length(SR6)

  if SR6(i) > upper || SR6(i) < lower % if outside of
deviation limits
```

```
    slip_Torque(ind) = TorqueFeedback6(i); % Torque read
from BAS
    slip_Speed(ind) = D2Motorspeed6(i); % Speed read from
BAS
    ind = ind+1; % increase indexing variable

  else
    Op_Torque(ind) = TorqueFeedback6(i); % Torque read from
BAS
    Op_Speed(ind) = D2Motorspeed6(i); % Speed read from BAS
    ind = ind+1; % increase indexing variable

  end
end

% Test 7 data analysis
for i = 1:length(SR7)

  if SR7(i) > upper || SR7(i) < lower % if outside of
deviation limits

    slip_Torque(ind) = TorqueFeedback7(i); % Torque read
from BAS
    slip_Speed(ind) = D2Motorspeed7(i); % Speed read from
BAS
    ind = ind+1; % increase indexing variable

  else
    Op_Torque(ind) = TorqueFeedback7(i); % Torque read from
BAS
    Op_Speed(ind) = D2Motorspeed7(i); % Speed read from BAS
    ind = ind+1; % increase indexing variable

  end
end

%% Create graph showing the ranges where the BAS was able
to operate without slip versus regions where it could not

Figure;
scatter(Op_Speed,Op_Torque,'k') % plot areas of normal
operation
axis([0 inf -60 60])
```

```
hold on;

scatter(slip_Speed,slip_Torque,'filled','r') % plot areas
of slip
axis([0 inf -60 60])
title('BAS Torque-Speed - Points of Slip')
xlabel('BAS Speed (RPM)')
ylabel('BAS Torque (Nm)')
legend('No Slip','Slip')
```